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Ocean Energy

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William H. MacLeish, *Editor*
Paul R. Ryan, *Associate Editor*
Deborah Annan, *Editorial Assistant*

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Editorial correspondence: *Oceanus,* Woods Hole Oceanographic Institution, Woods Hole, Massachusetts 02543. Telephone (617) 548-1400.

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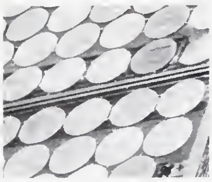

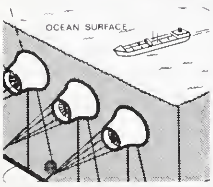

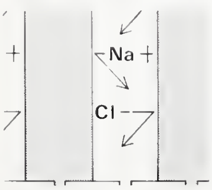

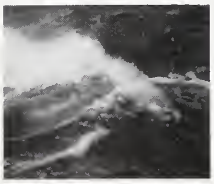

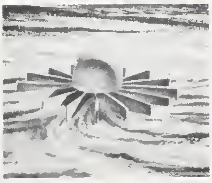

FRONT COVER: The sun setting over Penzance Point, Woods Hole, Massachusetts. Photo by Anita Brosius, © 1979: BACK COVER: Ocean scene. Photo by Gordon S. Smith, PR.

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The trouble with our time is that the future is not what it used to be.

Paul Valéry

Ever since the Industrial Revolution life in the developing world has been materially enriched and broadened, the pace has quickened, invention has become the mother of necessity, and all things have seemed possible. Industrialized man has thought of himself as apart from "nature," immune to natural constraints. But the earth is threatening comeuppances.* Problems of energy, pollution, resources, and food supply have shown up, and governments are beset by perplexities. Still, just possibly, all this can be forestalled if the nature of "nature" is understood and taken into account.

Ecological Imperatives

Nature abhors monocultures. It thrives on the diversity of species whose numbers are automatically controlled by the balances between their needs and the resources available at the time. It is a manifold system in which everything is used over and over in an interlocking pattern of living and inorganic processes. But with man as an aggressive, dominant species, the earth has ceased to be a self-contained ecosystem and has become a "resource." Man strives to manage the earth. But with every human intervention, the natural balance of everything, including man, is disturbed.

In the modern decision-making process, major enterprises are initiated by governments and industries solely on the grounds of economic, political, or military advantage. The natural consequences of these decisions are all but ignored — even those which affect human survival are dismissed as a "calculated risk." If humanity is to survive on earth, man must be recognized as a part of nature, and nature on earth considered to be "endangered." Clearly, (western) man must reconsider his place in the world — learn to live *with* the earth, not just on it — rearrange his affairs, his governments, and his decisions to suit the natural facts.

American government is more responsive to immediate pressures than to long-range problems. Yet given sustained emphasis on valid and properly delineated objectives, government can be moved bit by bit toward necessary social readjustments. Here natural scientists can help, not so much by problem solving as by problem definition: What are the basic conditions of nature into which social, political, economic, and industrial goals must be fitted to insure human survival? Framing the right questions involves so much study and understanding that quite often the answers are apparent, too.

The need for such study is already clear. We know, for example, how the release of fluorocarbons can influence the ozone layer in the high atmosphere and encourage the damaging transmission of ultraviolet light to life on the earth's surface. Steps have been taken to control that practice. We know, too, that large-scale release of carbon dioxide can influence the ability of the earth to radiate heat into space, the "greenhouse effect." But we don't know whether an increase of man-generated CO_2 will act as a radiation blanket and cause the earth to heat up (melting polar continental ice and raising sea level) or increase cloudiness, reflecting more sunlight into space, and thus cause the earth's surface to cool.

The solar-terrestrial heat balance is vitally important because only *liquid* water makes life possible. While water at sea level pressure remains liquid from 0 to 100 degrees Celsius, the life-sustaining range is only about 50 degrees Celsius. Considering that the universe as a whole operates through a range of millions of degrees, from the fierce cold of space to the inconceivable heat of stellar interiors, it becomes clear that earthly temperatures are both critical and precious. Therefore, we must preserve the earth's climates through knowledge and purposeful self-discipline.

The Energy Comeuppance

The word *energy* is much used these days, but not always in its physical sense. Energy, in physics, is the capacity to do work. Energy comes in many forms — mechanical, electrical, chemical, thermal, gravitational, radiative, and so on — but all forms can be put in just two classes: (1) *potential,* or "stored" energy, and (2) *kinetic*, the energy associated with motion. Each can be converted to the other and back again with no loss or gain. For instance, a gallon of gasoline (potential) can be burned in an engine to put a car in motion (kinetic) against friction and inertia, and up a hill against gravity. Here the car has gained gravity potential and is hot with thermal potential, but the sum of all the "energies" involved is just equal to the chemical potential of the original gallon of gas. The *rate* at which all this happens (work done per unit time) is *power.* This is the really important issue in the "energy" crisis. Power can be measured in watts.

Even if all available energy is transformed into heat, as is almost the case when food is eaten and metabolized, the rate of biochemical heat production can be measured in watts. For example, a man, sitting quietly, maintains his body temperature by burning food at a power level somewhere between 100 and 200 watts. When working hard, his metabolic power level rises to some 500 watts, but remains at the same order of magnitude; that is, hundreds of watts, expressed in powers of ten as 10^2. A fair-sized household can be kept comfortable in winter, and hot food served, at

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*Old-fashioned word for deserved rebuke or penalty.

a power level below 10,000 (10^4) watts; but when the ignition key of the family automobile is turned and the vehicle run up to cruising speed, the rate of energy expenditure is some 100,000 (10^5) watts! If we are to sustain ourselves without fossil or nuclear fuels, we must examine the power levels available in ordinary natural processes.

The greatest power resource available is sunlight, which reaches the earth's surface at a power level of 10^{16} watts. Sunshine drives all external earthly processes and sustains life. Power from the earth's interior (arising from primordial and radiogenic heat, or the more spectacular but less powerful volcanoes, geysers, hot springs, and earthquakes) has collectively a level of 10^{10} watts measured on a continuous basis, that is, smaller than the solar input by a factor of one million. Even rainfall is more powerful, at 10^{11} watts.

We have made a study of the world power levels in natural processes. The results are given in layman's terms (through the kindness of Fitzhugh Green, author of *A Change in the Weather,* W. W. Norton, 1977) in Table 1. Note, in reading through the list, that the power level demanded by modern civilization is 10^{13} watts. In human terms, the world power demand exceeds by one hundredfold the "food power" requirements of everyone alive today.

In Table 1 we find, perhaps surprisingly, that the plant kingdom, which stores sunlight in the form of organic chemical bonds mainly between carbon and ordinary water substance (photosynthesis), offers the greatest promise as a renewable energy resource. Plants yield food, and, with the action of anaerobic (anoxic) bacteria on plant residues, can also supply most of the fuels and fertilizers needed in mechanized agriculture. When we consider that the haphazard accumulations of coal, oil, and natural gas were built up by these photosynthetic and microbiological activities over the course of millions of years, it seems reasonable that the same processes may serve, under controlled conditions, to keep us going. If so, it is probable that the knowledge of botanists, agronomists, foresters, algologists, mycologists and so on, coupled with that of organic and industrial chemists, microbiologists, and their colleagues, will assume new importance. *The life sciences could lead us out of a technological dilemma.* The high-grade fuels (hydrogen, methane, alcohols) and manure-like fertilizers derived from organic stocks are compatible with existing petrochemical technologies and mechanized farming practices. The transition from fossil resources to day-by-day accumulation, storage, and distribution practices could be both natural and relatively easy. Moreover, the prospect is quantitatively adequate if we do not, just yet, exceed present levels of food and power consumption.

Wind power comes to Block Island, Rhode Island. The single large experimental wind turbine at top of hill was dedicated on June 15, 1979. It is capable of supplying 5 to 15 percent of the island's electricity, or more than $30,000 a year in fuel costs. It is the first federal government wind turbine on the East Coast, a preliminary step toward the production of electric power from locally available resources. It would take from 6 to 20 of these machines to make the island population self-sufficient in electricity. (DOE photo by Dick Peabody)

All this does not mean that physical alternatives are to be ignored or that there is but a single solution to the power crisis. Every use we make of locally available natural power — from winds, waves, tides, brine gradients, evaporation, ocean thermal stratification, great currents, or back-country mill races — will reduce the demand on the world total. This suggests that decentralized power production may eventually displace the systems concept in power generation and distribution procedures. Local autonomy could be delightful, restoring human scales of credibility to the modern living process.

There is also a need to match power qualities to uses. In a speech at the Tennessee Valley Authority, President Carter made the observation that it seems inappropriate to use a core temperature of millions of degrees or a flame temperature of thousands of degrees to raise the temperature of a room to 68 degrees Fahrenheit — there must be a better way. Without saying it specifically, the President made a distinction between the high-grade heat and fuels needed for transportation and industry, and the low-grade heat needed for life-support and husbandry. The

Table 1. Estimates of power levels in natural processes.

Available Sources of Power	*Total Power in Watts*
Direct solar power	
Where sun hits atmosphere	10^{17}
At earth's surface	10^{16}
Photosynthesis (Stores sunlight, in the form of chemical energy, in fats, proteins, and carbohydrates — all combustible.)	
Marine organisms	10^{14}
Arable lands, forests	10^{13}
Bioconversion of waste materials	
Plant residues and manure (Can be converted by bacteria to gaseous fuels — hydrogen and methane — by storing them in airless containers at proper temperatures.)	10^{12}
Garbage, sewage, and pulps (Can be converted by the same process.)	10^{12}
Ocean thermal power	
Solar heat absorbed by ocean water (Can possibly be put to use by exploiting temperature differences between surface and depths, producing power to drive turbines.) Atoll sites would be useful.	10^{13}
Steady surface-wind power, like that from trade winds (Atolls would be a good place to put very large windmills.)	10^{12}
Variable surface-wind power (in middle latitudes where winds are unsteady)	10^{12}
Hydroelectric power (from harnessing the kinetic energy of moving waters)	
Power in rainfall (Conceivably could be harnessed; but the world's total rainfall — even if you include the rain dropping on the oceans — would satisfy only 10 percent of the world's power demand.)	10^{12}
Flow of rivers (Harnessable by traditional hydroelectric plants)	10^{11}
Natural evaporative exchanges between large bodies of water (Mediterranean Sea and Red Sea are examples: evaporation is greater in them than in the ocean at large; therefore, there is a continual flow into them from the oceans to replace evaporated water. This flow can be harnessed, just as in a mill race.)	10^{9}
Damming of evaporative sinks. (By damming ocean openings to Red Sea and Mediterranean Sea, letting these seas evaporate until a drop of 100 meters or more occurs, and then letting the ocean flow in, turning mill wheels, additional power might be obtained. Not very practicable to build these dams, however, because of earthquakes.)	10^{11}
Tidal flow (Particularly at places like the Bay of Fundy, where flow can be harnessed.)	10^{9}
Power of great ocean currents like the Gulf Stream and Kuroshio. (Theoretically these can be harnessed the way rivers are, with some sort of "water wheel.")	10^{8}
Ocean surface waves at coastline (Power of waves is available at a potential average yield of 10^{6} watts per kilometer of coastline.)	10^{10}
Geothermal power (Particularly at the "ring of fire" around the Pacific Ocean basin, so called because this is where tectonic plates merge and volcanoes erupt; the same happens along mid-ocean ridges.)	10^{10}
Present Power Demands	
Worldwide power demand for all needs of civilization	10^{13}
Human metabolism (Total power in terms of food needed to sustain present population level of 4 billion.)	10^{11}

production, collection, and storage of low-grade heat in sensible or latent forms is an interesting new field of technology and enterprise.

About half of the power produced for modern society goes to heavy industry, and the other half goes to food production and domestic uses. *While the fuels are the same for both, they ought not to be.* Compact, high-energy fuels producing temperatures above red heat are needed for transportation and industry, but high-energy fuels are wasted when used for space heating, hot water, drying, culturing, or other low-temperature services. Industrial waste heat or even the heat of daily sunshine, collected and stored underground in natural reservoirs, could serve low-grade heating needs just as well.

Electric power is a separate issue. Electricity is so convenient we tend to use it inappropriately as a low-grade fuel for space heating and hot water, when actually it is a very high-grade fuel. Electric power production, other than hydroelectric power, is inefficient. A coal or oil-fired plant consumes three times as much power in heat as it puts out in electricity. Half of this output is lost in transmission lines and most of the power delivered is used at 50 percent efficiency, bringing the overall efficiency of

electric power usage down to about 8 percent — that of an old-fashioned steam locomotive. Moreover, network electricity is "fresh" power, produced for immediate consumption at rates which follow the rise and fall of demand. Electricity should be thought of as a luxury and be employed only where electricity alone will serve. It is too wasteful of fuel to do otherwise. Hydroelectric power, while independent of fuel constraints, is already more than half developed in the world. So there again, even hydroelectric power should be used only where electric power alone will serve. Solar photovoltaic electricity may change these constraints when it is more fully developed.

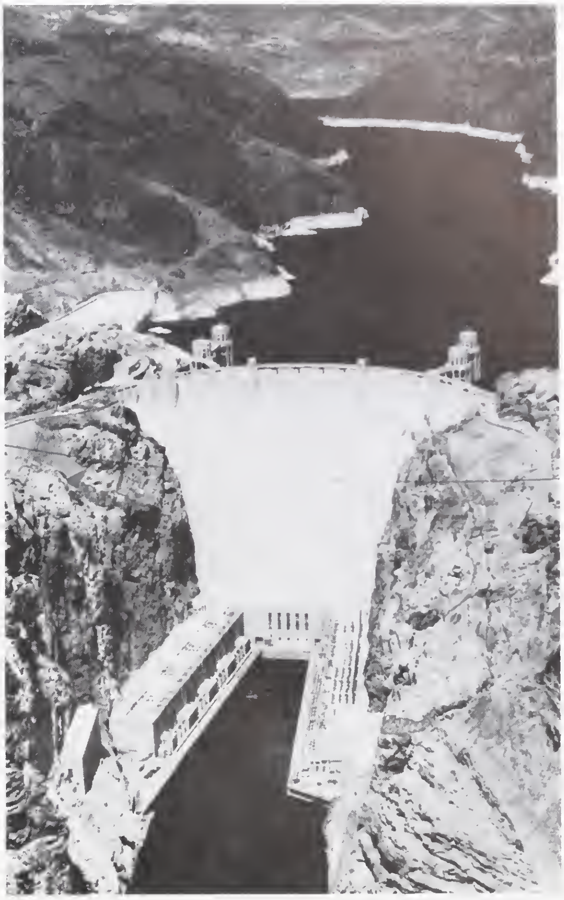
Taking the world as a whole, the global power demand at 10^{13} watts is only one one-thousandth part of the power available in sunshine reaching the earth's surface. But even at present levels of power and heat production, we find "thermal islands" around cities and, through deforestation, farming, and blacktopping, a change in regional climates. While we have yet to change *global* climates very much, the possibility exists in the indiscriminate release of *new* heat on the earth. We know from studies of the general circulation that the patterns of flow in oceans and atmospheres can be altered when the heating and cooling patterns are changed and that these patterns show marked hysteresis. Once altered, each system has to be forced far more powerfully in the opposite direction to recover. This suggests that the works of man should be governed to stay within the limits of existing balances.

In a solar powered era, we would be moving heat from place to place and releasing it at times quite different from the natural course of events; but we would not be *adding* heat to the earth as we have in the fossil or nuclear fuel period, we would be simply *diverting* power and heat from place to place and time to time without changing the average annual budget. This might be a safe enough practice to risk a tenfold increase (to 10^{14} watts) in a world total power demand, but that risk should be well calculated before it is taken.

The risk also may be postponed. Much of the world's energy supply ends up as heat; indeed, high-quality fuels are used to produce just that, *heat.* Fuels could be saved by simply placing industries in thermal cascades, the exhaust heat of one being the input heat to the next, with the chain ending in space heat and hot water for human comfort. There would then be no such thing as "waste heat," and industrial cooling facilities might be ruled out of further consideration in energy systems planning.

The Pollution Comeuppance

Pollution is mainly an economic disease. It has been said that the solution to pollution is dilution, but the immediate question is *by what?* There is air, water,



Hoover Dam stores water for hydroelectric power production from the Colorado River, but suffers enormous losses of capacity as the result of evaporation and silting. (Photo courtesy DOE)

solid earth, and space. Of these, only space has limitless capacity. Ultimate disposal in space is, at present, prohibitively expensive. Disposal at sea and in the solid earth is conceivable economically and is actually practiced, but more commonly, wastes are simply dumped, or let go into the atmosphere and water courses nearby. The atmosphere and hydrosphere are both showing signs of such loading because the rate of discharge into them exceeds their abilities to store pollutants at safely low levels or to deposit rapidly enough the unnatural quantities of material discharged into natural sinks.

The ocean has been dubbed the largest sewer to which man has ready access. An international group of scientists has looked into this "sewer" to establish present levels of natural and man-made solutes, suspensions, and precipitates. For some purposes, the world ocean is full. Some areas are even "posted." Moreover, within the past few decades a surface film of oil has become so

The sun's energy is being used to produce power for an experimental irrigation project near Mead, Nebraska. The system's 120,000 individual cells produce 25 kilowatts of electric power at peak sunlight, which is used to drive a 10-horsepower pump that helps irrigate 80 acres of corn and soybeans. (Photo courtesy DOE)

ubiquitous that changes in the normal rate of exchange of gases into and from the atmosphere are probable. Petroleum spills reaching beaches and wetlands pose a threat to marine life and its utility as food. Heavy metals are also known to accumulate in marine foodstocks. But these effects can be managed by rooting out their causes and spending what is needed to scrub, treat, purify, or otherwise neutralize harmful wastes. There are no insuperable problems other than the economics of cleaning up as we go.

Radionuclides are altogether different. The half-lives of some radioisotopes are longer than the history of civilization. Ultimate disposal of these materials must take into account both the attention span of whole civilizations and geologic time scales. Beyond economics, space disposal in nonsolar orbit seems attractive; but what happens if a launching fails? Burial in the continental ice caps of Greenland or Antarctica, from which re-emergence may be measured in tens of thousands of years under present climates, has been considered; but what about spills en route, and who would warn future generations about re-emergences? Burial in sea-floor trench sediments near zones of subduction has been suggested; but subduction zones give rise to volcanism in island arcs which might, after some time, bring half-spent radioactive materials back to the surface. Burial of vitrified wastes in geologically quiet sites has been suggested and even done in salt beds, but at some risk. The matter is worrisome and far from settled. The memory of man is short, records easily misplaced or forgotten, and mining for some as yet uninteresting mineral or new resource could carry enterprising men of the future into radiological danger. The true solution to ultimate disposal must be not only exceedingly wise but absolutely foolproof. Nothing less will do!

Resource Comeuppances in Food Production

Fresh water is in increasingly short supply in many agricultural and urban areas. This shortage is not due to a deficiency in the global water supply, but rather to a mismatch between regional demands and the climatological abundances of fresh water.

The fresh water volume on the earth is some 4 million cubic kilometers. Of this, the atmosphere holds some 1,400 cubic kilometers as vapor. The continental glaciers of Greenland and Antarctica and the high latitude permafrost regions hold some 3 million cubic kilometers, or three-quarters of the earth's fresh water, as ice. The world ocean holds some 1.2 billion cubic kilometers of salt water. This puts the ratio of abundance of *liquid* fresh water to seawater at about 0.3 percent. Of this amount, some 400 thousand cubic kilometers, or less than half of the world's supply of liquid fresh water, is recycled each year (through sublimation, transpiration, evaporation, and precipitation) to purify fresh water as a renewable resource. Three-fourths of this distilled annual supply of potable water falls back as rain on the oceans. One-third of the rain on land runs off to the sea in rivers, some "soaks in," and some is evaporated. Even so, the annual allowance for life support on land is more than 10,000 cubic kilometers, enough for many times the demand of present farms and world populations. But this water isn't always available where and when it is needed. Fresh water needs management and husbandry.

Management practices usually have been approached as a two-dimensional problem — shortages being met by pumping water across the country through pipelines or open trench aqueducts. To make the best use of potable water, it has been suggested that gray water be used in sewage systems and as slurry water in some industries. Along coastlines seawater may also be used as "process water" if its fouling and corrosion propensities are allowed for. And there is an additional prospect, that of water management and husbandry in three dimensions.

A great resource of good quality water (many times bigger than the annual supply) is stored in permeable sediments below ground. It is standard farming irrigation practice to pump this stored water to the surface, which lowers the water table. To restore supplies, the reverse also can be done — inject imported water into recharging wells and raise the water table. Water stored underground takes no land area away from farms, does not freeze in winter, evaporates only very slowly, and does not overturn in late summer as does water stored in surface reservoirs. A balance of discharge and recharge would not have to be met on a day-to-day basis but could be averaged out over the year. According to water supply geologists, wells shallower than 760 meters would avoid the salt concentrations sometimes found in deeper aquifers.

Years of study and experiment have gone into the water distribution problem through the fields of weather and climate modification. This work has attempted partly to learn how to suppress the severe storms that threaten crops and populations, and partly to "steer" the weather

A self-propelled irrigation system near North Platte, Nebraska, capable of working 160 acres in 24 hours even though a large portion of the water supplied is lost through evaporation of the spray. (Photo by Joe Munroe, PR)

patterns which collectively determine climate. The basis for many experiments is that meteorological processes are non-linear and that small influences at the right place and time can produce large (desirable) consequences. While many interesting phenomena are now known or are becoming understood, routinely practicable weather and climate control practices are still out of reach. For now, we must make do with water supplies as they are.

Next to water in urgent need of resource management is soil. Arable land takes thousands of years to mature and is necessary to life. It should not be buried under suburban developments, new cities, airports, parking lots or roads, be laden with road salt, pesticides or chemical wastes, or have its topography changed to such an extent that soil horizons are severely disequilibrated, as by strip-mining.

Soil is a chemically and biologically complex medium capable of sustaining polycultures. The Green Revolution seeks to establish high-yield, hybrid crops as monocultures, prime for mechanized cultivation and harvesting, but is heavily dependent on irrigation and petrochemicals to prevent polycultural intrusion and soil nutrient depletion. The Green Revolution has raised yields some three or even fourfold per acre and, with mechanization, reduced the human labor of production, but not the cost of food or its availability to hungry populations. Under less artificial and intensive farming practices, soil can be maintained as a living resource.

Automobility, San Francisco Bay Bridge, California. (Photo by Joe Munroe, PR)

Marine aquaculture, a necessary next step in feeding a hungry world, depends not only on water chemistry, temperatures, and circulation, but on the qualities and quantities of organic matter and textures in the "soil" of sediment. Coastal sediment transport, nutrient transport, thermal cycling with season and other normal changes can be abruptly modified by a single storm. Indeed, all the changes in the physical, chemical, and biological condition of inshore waters and sediments between storms are found to be small compared with the effects of just one major storm. It seems necessary, therefore, to study coastal processes in bad weather even more intensively than under average conditions if the operating requirements of marine aquaculture are to be known and faced as routine procedure.

The world ocean provides some 10^{10} metric tons of organic fixed carbon each year — enough to feed a world population of 10 billion and then some — and a very large part of this production occurs in the neritic zone convenient to shore — enough to feed the present world population of 4 billion. But harvesting this yield is not easy.

Most of the edible biomass in the ocean is in the form of microscopic organisms, diluted by sea water to 1 part per million (by weight). The technical difficulties of filtering very large volumes are beyond the economic reach of man, but not beyond the survival skills of finger-size filter feeders which tend to school. Schooling concentrates marine life and provides a practical basis for harvesting in the menhaden, anchovy, and sardine industries. Concentration in two dimensions also occurs in harvesting demersal fish and sessile organisms in the dragger industry. Long-line fishing and mid-water trawls catch the delicious, meaty table stocks in blue water offshore and on banks at some profit. But all of these together (even including "trash" fish catches) fall far short of meeting the present world food demand. Aquaculture, to be an effective food producer, must be designed to grow and harvest biomass close to the bottom of the food chain. This makes aquaculture a very large-scale enterprise.

Aquacultural "produce" is likely to be in the form of dried meal, a food additive to agricultural production. It must be "sold" to become an acceptable food. Starvation has been known to occur because of dietary preferences and taboos. But, though populations are increasing and agricultural production will be declining owing to land abuse, fresh water shortages, and petrochemical depletion, aquaculture and agriculture working together may just get us by. Finicky appetites will disappear (by natural selection) as the Malthusian limit is approached.

Lifestyle

Just as "nature" abhors monocultures, so too should human societies. The lifestyle of no one culture is yet so perfect or ideal that it should be imposed upon or even imitated by another. Local and regional differences of environment, the history of each culture, traditions, all lead to a variety of demands upon and adaptations to nature. This variety spreads the demands of mankind over a wide range of natural supplies — so different from the case in western cultures, where everyone wants the same things.

The profligacy and wastefulness of the American lifestyle is probably not innate but induced by advertising and status symbology. Most people are willing to help by recycling, cutting back on fuel demands, being obedient in the face of authority, kind, even compassionate, when occasion demands . . . but in his automobile Everyman becomes a *tiger.* Here is raw power and status all rolled into one. Automobility has become a social focus around which much of the world's lifestyle has been built or imitated. The problems of urban sprawl, rush hours, supermarket and shopping center development, broad swaths and long sweeps of blacktop across arable land, decay of

public transportation and the need for countless bridges can all be traced to the automobile. What can be done about it? Probably not much; the elements of privacy and self-determination are too strong. But from it we learn how significant the motivations for privacy and self-determination can be in human beings everywhere.

In a world of naturally renewed abundances, the words *change* and *reassignment* will be heard more often than *growth* as it is used today. Still, growth of personal significance and self-esteem may well result from a lifestyle in which individual effort and responsibility have clearly established meaning, which is to say that all proper designs for living must recognize the social as well as the material needs of life. People like to move about, encounter friends by chance, be assured of privacy when the mood prevails, feel secure in the expectation that self-determination plays an important part in guiding daily events, and believe that the future offers challenging but hopeful prospects.

Designs for the Future

Concern for the future of mankind has always been in the minds of thoughtful people. In recent years, Aldous Huxley's *Brave New World* gave warning that logical extensions of contemporary trends could lead us into the maddening technocracy of "centrifugal bumblepuppy." George Orwell's "Big Brother" added to the theme in his novel, *1984,* a date which is now close upon us. Following these conjectures, E. F. Schumacher took serious issue with the trends of the '70s in his book *Small is Beautiful,* subtitled *Economics as if People Mattered,* and gained a widespread following. Alvin Toffler's *Future Shock* treated the effects of rapid, overwhelming change on people's lives and states of mind. What to do about it all has been suggested in Lester Brown's *World Without Borders,* Paul Ehrlich's *The End of Affluence,* and even more salient thrusts are found in Amory Lovins' *World Energy Strategies* and in his *Soft Energy Paths.*

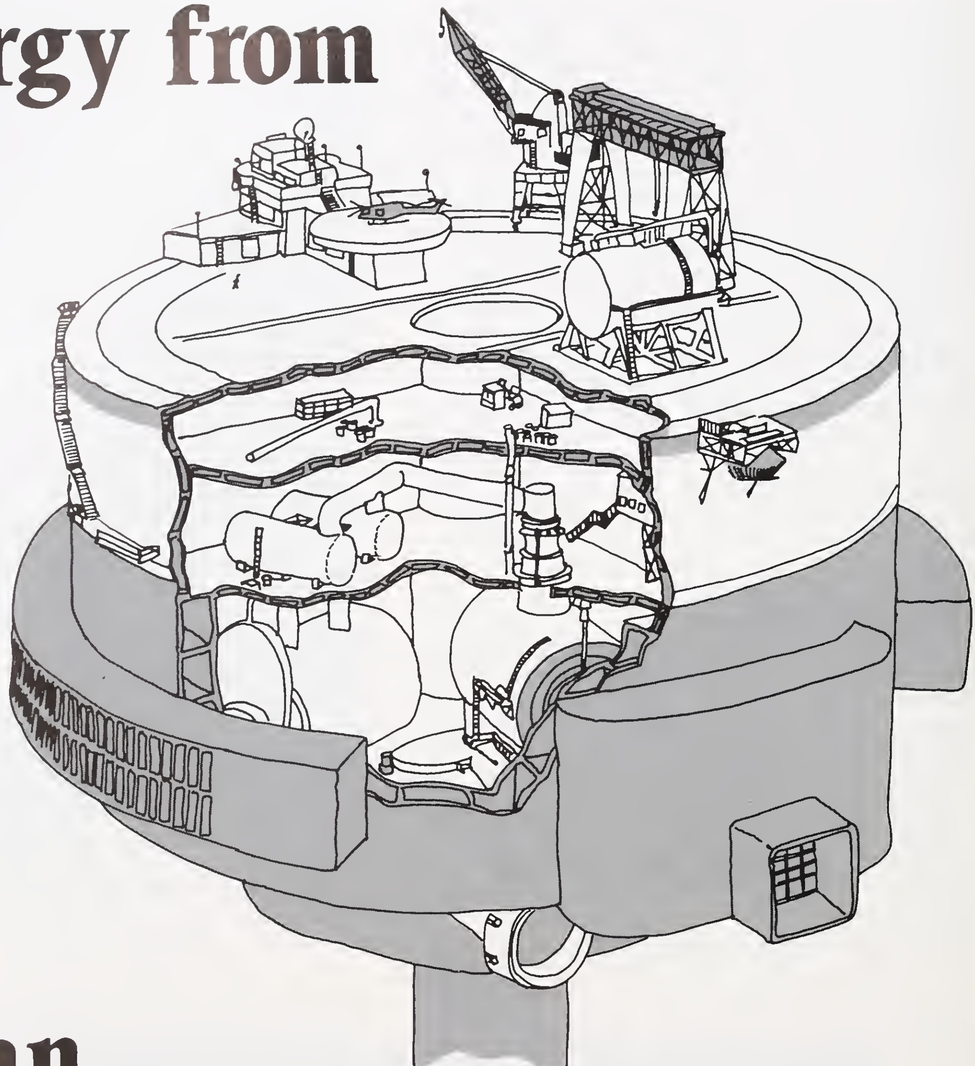
Within this gathering storm of very keen thinking and good writing there is a scholarly and intensely penetrating Porter Prize thesis (Yale '73) by William Ophuls, published by W. H. Freeman, 1977, under the title *Ecology and the Politics of Scarcity; (Prologue to a Political Theory of the Steady State).* Ophuls' book must be read twice and thoughtfully; once for the text and a second time for the boxed "footnotes."

Along with these bound works are the less formal essays by Barry Commoner in *The New Yorker,* 2, 9, 16 February 1976 and 23, 30 April 1979; the Alaskan view by Seifert and Leonard in *The Northern Engineer,* 9 (4) 19-25, 1979; Amory Lovins' early paper in *Foreign Affairs,* 55 (1) 65-96, October 1976; and finally J. H. Plumb's perceptive statement in *Horizon,* XIV (3) 4-9, 1972, "An Epoch that Started Ten Thousand Years Ago is Ending." To regain perspective in this sampling of the "Future of Man" literature it may be well to reread Harrison Brown's *The Challenge of Man's Future,* Rachel Carson's *Silent Spring,* Stewart Udall's *The Quiet Crisis,* top it off with Marston Bates' *The Forest and the Sea,* and then think about what needs to be done.

William S. von Arx, Senior Scientist Emeritus, has been engaged in research and teaching at the Woods Hole Oceanographic Institution since 1945. He is currently involved in solar energy research.

(Photo courtesy DOE)

Energy from



Ocean Thermal Gradients

by Robert Cohen

Among the renewable geophysical energy resources present in the sea, ocean thermal gradients are the least conspicuous. To the casual observer, other ocean energy sources, such as waves and tides, hold the most obvious potential, and devices can even be quickly envisioned for harnessing these types of power. Popular press accounts to the contrary, the conversion of ocean thermal energy is not complicated — visualize a household refrigerator cycle and then reverse it. Actually, fuel-free ocean thermal energy conversion (OTEC) power cycles are simpler than those of conventional power plants, which require conversion of fuel into heat.

The concept of utilizing ocean temperature differences to generate electricity is not new. It was first proposed by Arsène d'Arsonval, a French physicist, nearly 100 years ago (1881). He advocated using warm, solar-heated surface waters to cause a working fluid such as ammonia to evaporate, thereby forcing the rotation of a turbine attached to an electrical generator (Figure 1). Cold, nearly freezing water, pumped up from 1,000-meter depths, is then used to reliquefy the ammonia vapor, and this "closed cycle" is repeated. The devices employed to transfer heat between the water and the ammonia are known as an evaporator and condenser, respectively. Such devices are usually referred to as heat exchangers. They are a key cost factor in constructing a closed-cycle OTEC power plant, since large quantities of water must be circulated past heat exchangers to produce significant yields of electrical energy. This is because there is a low conversion efficiency intrinsic to utilizing such small available ocean temperature differences (typically about 20 degrees Celsius) for the production of electricity.

As an appealing potential source of substantial amounts of electrical energy, OTEC technology is now being examined to establish whether it is viable from technical, economic, and environmental viewpoints. As with other renewable energy options, a key question for OTEC is the relative cost projected for OTEC energy compared to the rising cost of energy from depletable energy sources.

Because the oceans act as a natural collector and storage device for thermal energy derived from solar radiation, the ocean thermal resource is steady day and night; hence, OTEC electricity can be produced continuously. Power plants continuously generating electricity are known as baseload plants. OTEC power is one of the few solar energy options (hydropower and ocean currents are others) that can provide a source of baseload electricity. Accordingly, the cost of OTEC-derived electricity must be compared with the cost of electricity from other baseload sources, such as coal and nuclear power plants.

Although the ocean thermal resource can be utilized via aqueducts at land locations abutting the ocean, adequate thermal gradients are mainly accessible at sea. Figures 2A and 2B indicate promising geographical areas in tropical and subtropical latitudes for OTEC sites. Two key options for utilizing OTEC electrical power generated at sea are 1) to transmit the power to shore via submarine electric cable and 2) to manufacture energy-intensive products aboard the platform, such as aluminum, ammonia, hydrogen, chlorine, and magnesium. The electricity-to-shore option requires precise platform station-keeping, whereas the product option does not. Because of the global energy conversion potential of the ocean thermal resource, OTEC is being developed by the governments of France, Japan, and the United States, by a consortium of European industrial firms known as EUROCEAN, and by an industrial consortium operating the Mini-OTEC experiment in conjunction with the State of Hawaii. The other programs are rather modest compared to the U.S. government's OTEC development program, which was budgeted at $38 million during fiscal year 1979.

First experimental studies of utilizing ocean

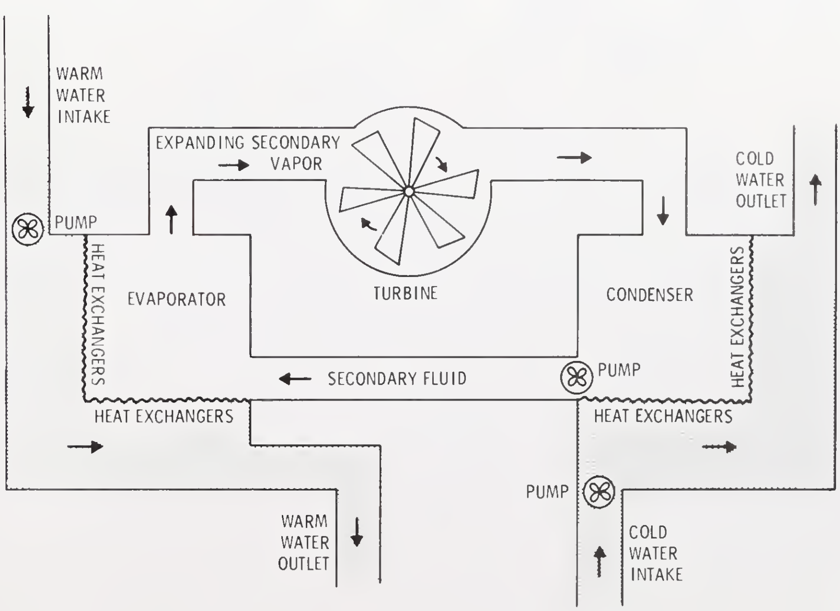


Figure 1. An OTEC closed-cycle system.

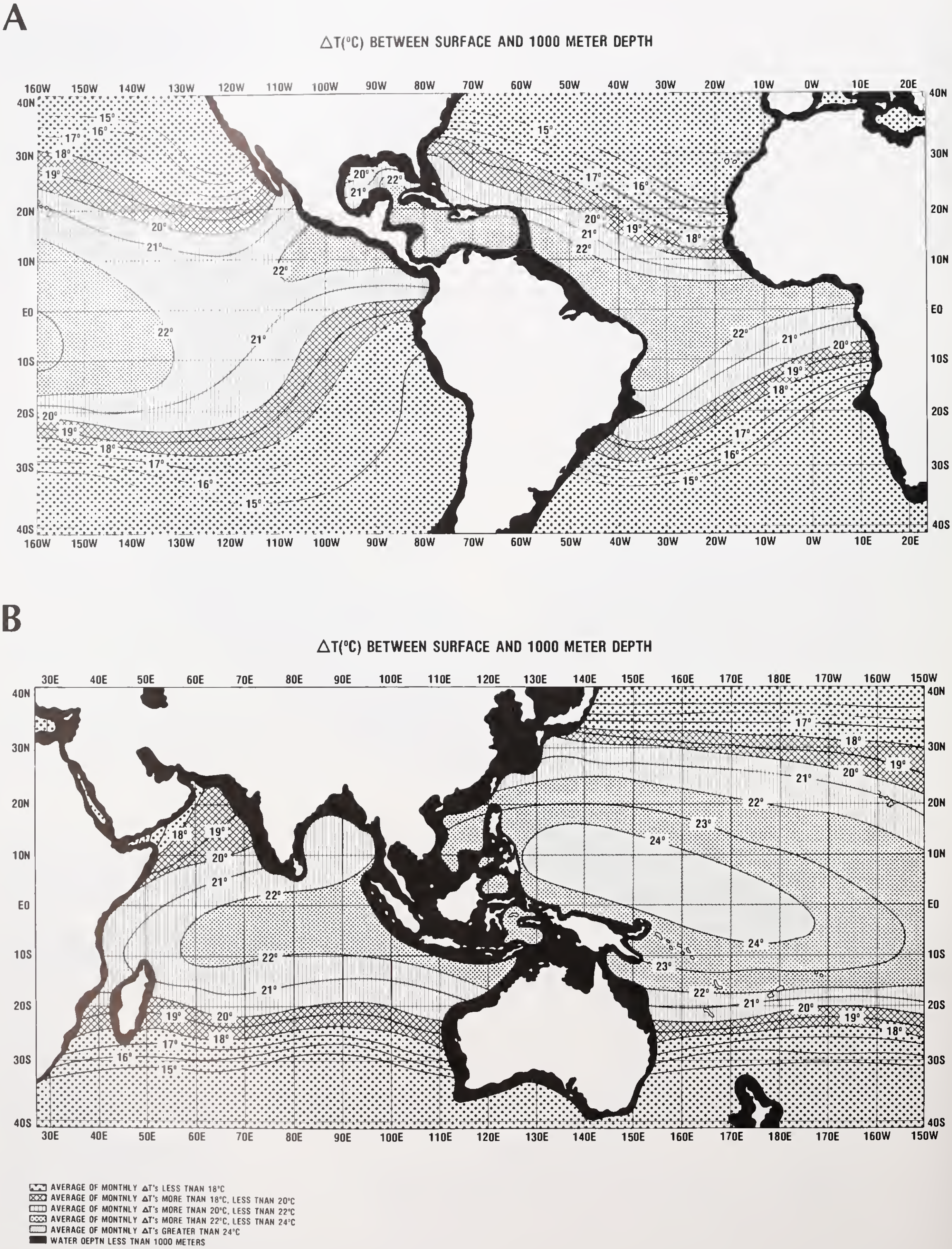


Figure 2. Contours showing the annual average monthly temperature differences (in degrees Celsius) between the ocean surface and depths of 1,000 meters for (A) the Western Hemisphere, and (B) the Eastern Hemisphere.

thermal energy were conducted by the French inventor Georges Claude off Cuba, reported in 1930. Claude's experiments employed an open-cycle system, wherein seawater was used as the working fluid (Figure 3). By operating under a partial vacuum, the ocean surface temperature is adequate to "flash-evaporate" seawater, the escaping steam causing the rotation of a turbine wheel connected to an electrical generator. The spent vapor is then cooled in a condenser by cold water pumped from depth. This power cycle derives its name from the fact that the condensate need not be returned to the evaporator, as in the case of a closed-cycle system.

Both the closed and open-cycle systems hold promise for commercial applications. However, researchers in the United States regard the state of development of open-cycle technology as being less advanced (by several years) than closed-cycle technology. Because of the need in the open cycle to harness the energy in low-pressure steam, extremely large turbines (comparable to wind turbines) must be utilized, and degasifiers must be employed to remove dissolved gases from the seawater. Recent open-cycle studies by the Westinghouse Corporation are encouraging, pointing to cost-effective solutions to turbine and degasification problems.

A closed-power cycle is being employed in Mini-OTEC, an experimental 50-kilowatt electric (KWe) gross power, barge-mounted ocean thermal power plant, which went into operation August 2, 1979, off Ke-Ahole Point (located northwest of the big island of Hawaii). The plant — not an optimized system — is testing key power system components under ocean conditions, while producing about 10 KWe of net power. Funding — about $3 million — is being shared by the State of Hawaii and a consortium of three corporations — Lockheed, Alfa-Laval, and Dillingham. The results of the experiment will be proprietary to the sponsors,

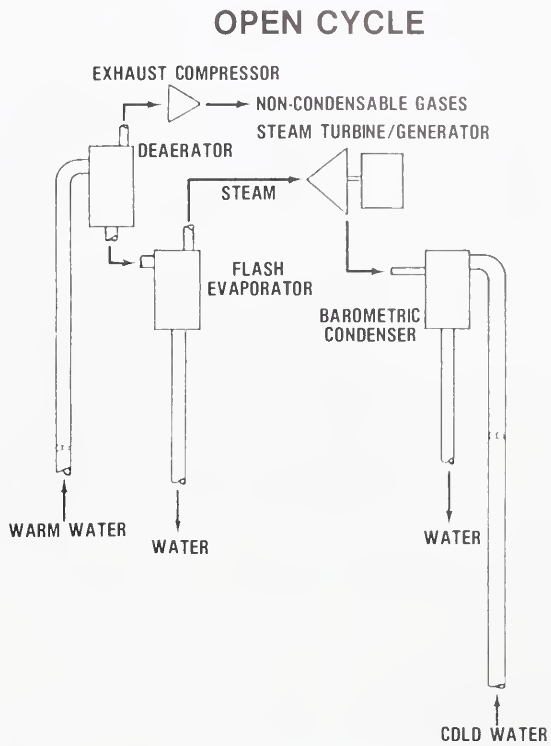


Figure 3. An OTEC open-cycle system, using flash evaporation of seawater.

although they will be made available to the U.S. government, which provided the vessel (Figure 4).

Closed-cycle power systems and their associated heat exchangers present several technical and cost challenges. The exchangers must transfer heat cost-effectively, and there must be a viable way to protect them against corrosion and biofouling layers, both of which inhibit heat transfer. The selection of titanium or stainless steel

Figure 4. The Mini-OTEC experimental power system on the deck of a U.S. Navy barge, alongside its buoy off Ke-Ahole Point, Hawaii. (Photo courtesy Lockheed Ocean Systems)

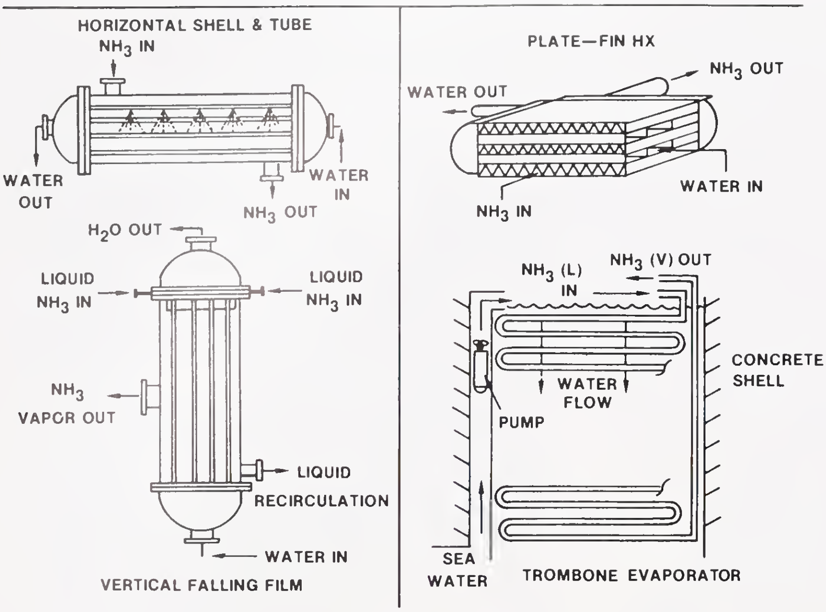


Figure 5. Shell-and-tube and plate heat exchanger designs under consideration in the U.S. OTEC development program.

as heat exchanger materials would minimize the corrosion problem, although alloys of aluminum are less expensive and may be adequate. Copper-nickel alloys resist biofouling formation, but may not be compatible with ammonia, the most attractive working fluid for closed-cycle power systems from an economic standpoint. Other possible working fluids are propane and fluorocarbons.

Extensive at-sea testing near Hawaii and in the Gulf of Mexico has been underway for several years to establish biofouling rates and countermeasures. Techniques for removing slime formations are being studied at several locations for various heat exchanger configurations. Heat exchangers fall into two main geometric categories: shell-and-tube and plate. Several examples in each category are depicted in Figure 5. Biofouling of tubular shapes can be cleaned by passage of brushes and spongy spheres through them. Chemical and mechanical techniques can be used for cleaning plate configurations.

The performance of both varieties of heat exchangers is being measured in the laboratory, and through core tests of large units rated at one thermal megawatt. The core tests are conducted at Argonne National Laboratory, Argonne, Illinois, which is operated for the U.S. Department of Energy by the University of Chicago. Testing of units up to forty times larger (1 megawatt electric) is scheduled to begin off Hawaii in April, 1980, aboard OTEC-1, a T-2 tanker being converted to serve as an engineering test facility. OTEC-1 will obtain performance evaluation of candidate heat exchangers and biofouling countermeasures under ocean conditions (Figure 6).

Core testing at Argonne of OTEC heat exchangers has proved encouraging, in that heat transfer rates are being attained that are more than twice those for standard industrial heat exchangers. This improved performance is obtained by augmentation of the heat transferred per unit area, through the use of special surface shapes and coatings. However, such enhancements must be cost-effective and sustainable at sea, which means that the cleanliness of the exchangers must be maintained in the presence of biofouling organisms.

Among OTEC closed-cycle subsystems, the technical viability and cost of the heat exchangers are key factors, since they can represent up to half the total plant investment. Other OTEC subsystems present technical problems that also must be solved at reasonable cost. In particular, viable solutions must be found for designing and deploying OTEC cold-water pipes and submarine cables. Candidate cold-water pipe materials include fiberglass-reinforced plastic (FRP), elastomers, and lightweight concrete. Pipe lengths of about 1,000 meters will be required, with diameters of about 10 meters for a 40-MWe (net) power output, and about 30 meters for a 400-MWe power plant. Submarine power cables rated at 100 MWe or greater, including bottom cables and riser cables, will need to be designed to withstand unprecedented electrical and mechanical stresses.

Various platform configurations have been considered for commercial OTEC power plants, including ship shapes and submersibles, such as spar buoys. For example, a 100-MWe surface

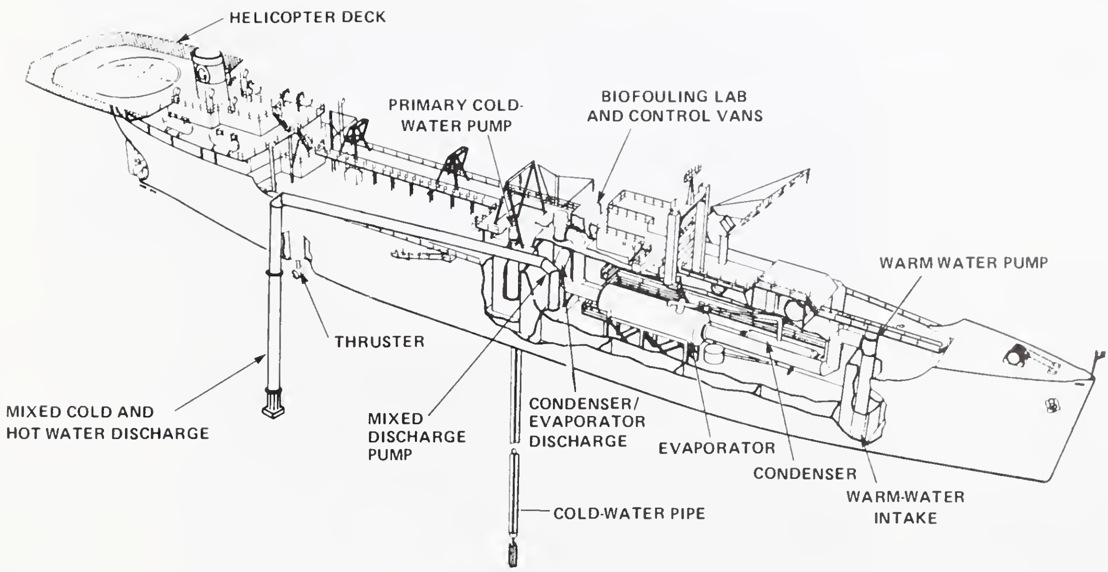


Figure 6. Chepachet, *a T-2 tanker, is being converted for use as OTEC-1, a 1-MWe engineering test facility for evaluating candidate heat exchanger designs.*

platform concept is shown in Figure 7. Station-keeping can be achieved by dynamic positioning or mooring, and is of special significance for electricity-to-shore applications. Other siting considerations involve ocean thermal resource requirements, market potential and logistics, possible impacts on the environment, possible impacts of the environment on plant design and operation, and — where submarine cables are employed — sea-floor conditions between the plant and the shore. The ability to withstand severe weather conditions, such as hurricanes, may necessitate the use of a submersible platform design, such as a spar buoy concept (Figure 8).

The OTEC development program includes testing of component hardware, subsystems, and complete systems so that technical unknowns can be resolved experimentally. A pilot plant is planned so that performance and reliability data can be obtained from a complete 10 to 40 MWe system. Conceptual designs for such a plant have been considered in a spar-buoy, ship, and land-based configuration. In addition to providing technical performance data, the pilot plant will allow a more accurate projection of costs for commercial OTEC power plants in the 100 to 400 MWe range.

The capital cost of commercial OTEC power plants will determine how competitive this source of energy will be in relation to other options. Based on available estimates, a reasonable target capital cost for the eighth OTEC production unit in the 100 to 400 MWe size range is projected to be about $2,000 per kilowatt (1978 dollars). However, costs may well exceed the target by up to 40 percent, or could be up to 20 percent lower. This estimate applies to the electricity-to-shore option, including the cost of a submarine cable system (about $300 per kilowatt), for a plant located 140 nautical miles west of Tampa, Florida.

Since OTEC, like other solar energy technologies, does not require fuel for plant operation, the major cost component is for amortization of the capital investment. Annual operation and maintenance costs have been estimated at 1 percent of the capital investment. Projected energy costs for the range of capital costs just stated are between 38 and 55 mills per kilowatt hour of electricity. This is comparable to costs projected for other baseload power sources, such as coal and nuclear, in the Gulf Coast electrical market for the years 1990 to 2000.

The first OTEC power plants, however, will be more expensive than later units, meaning correspondingly higher energy costs initially. Fortunately, electricity markets exist for the first OTEC plants, specifically such islands as Puerto Rico and Hawaii, where most of the electricity is derived from the combustion of oil. The capital costs for OTEC plants at such locations would be less than those for plants off Gulf Coast states, both because the ocean thermal resource is somewhat better at these locations and the power cables would need to extend only 5 to 10 kilometers from shore. Accordingly, even the first OTEC commercial plant is expected to be competitive in 1990 against the oil alternative in a location such as Puerto Rico (Figure 9).

Although the electricity-to-shore-via-cable option appears to be the OTEC application nearest to being commercially competitive, the

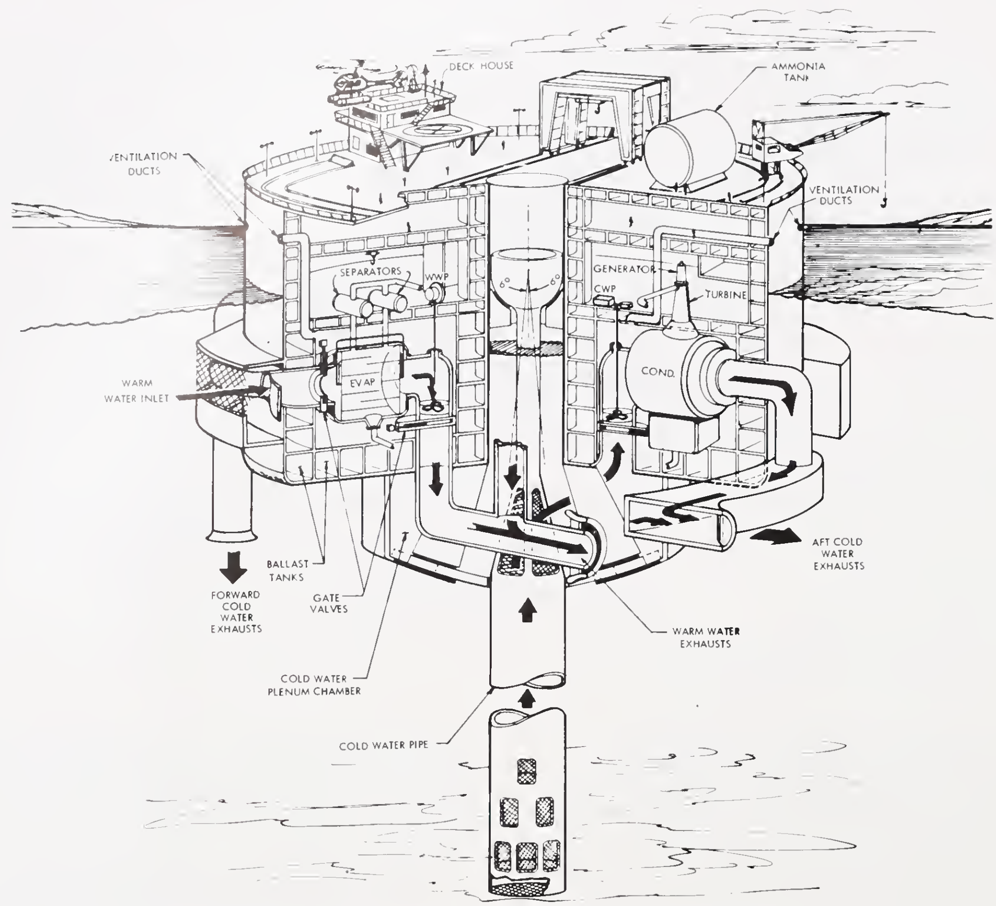


Figure 7. TRW, Inc., an ocean systems company in California, designed this 100 MWe OTEC power plant. The drawing shows a cutaway of one 25 MWe power module. The platform is about 100 meters in diameter.

manufacture of energy-intensive products aboard OTEC plant ships also has promising market potential. Aluminum, ammonia, chlorine, magnesium, and other sea chemicals are likely products. Some of these products could provide fertilizers, fuels, and feedstocks, or serve as a means to convey electricity to shore. For example, hydrogen or ammonia could be shipped to shore and reconverted to electricity in fuel cells. This possibility could be regarded as an "electrical bridge," providing OTEC with a means for serving distributed electrical markets, including the provision of peaking power to electric utilities. Another emerging market is batteries for the propulsion of electrical automobiles. Candidates for such batteries include lithium/air and aluminum/air. OTEC plants would ship bulk aluminum or lithium for this application, recycling the resulting aluminum and lithium hydroxides or carbonates, thus providing an "aluminum bridge" or "lithium bridge."

If the stability of OTEC platforms is compatible with the onboard refining of alumina, then OTEC-derived aluminum may become a viable product. On the other hand, aluminum could be produced on shore by utilizing OTEC electricity supplied by cable, especially at island locations convenient to sources of alumina or bauxite. Similarly, manganese nodules could be refined at sea on OTEC platforms near sites where they are mined, or could be refined on shore with OTEC power brought by cable.

Two possible OTEC by-products may be marketable: 1) fresh water, and 2) shellfish, kelp, or other crops that could be grown utilizing the nutrients upwelled in the cold water circulated through OTEC condensers. If the market value of these by-products exceeds the cost of producing them, then the economics of OTEC energy production could be benefited. However, the market potential for fresh water is tied to geography, and the utilization of the nutrient-laden cold water for open-ocean mariculture may be incompatible with efficient OTEC power plant operation because of possible recirculation problems.

Estimates of sustainable OTEC power that could be extracted from the ocean thermal resource

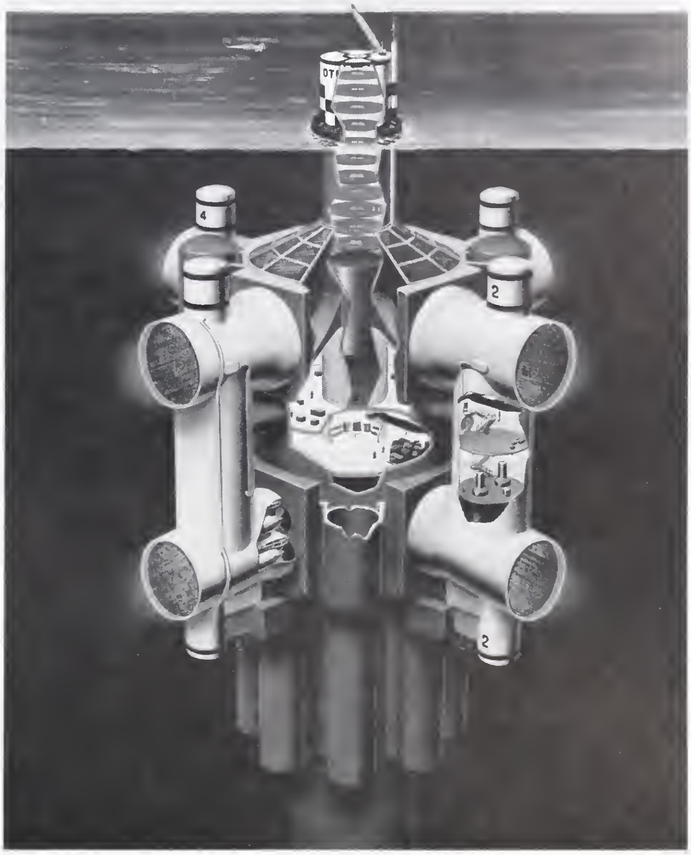


Figure 8. A Lockheed Corporation concept of a 160-MWe submersible OTEC platform. (Photo courtesy Lockheed Missiles & Space Co., Inc.)

in the Gulf of Mexico indicate that 200,000 MWe or more may ultimately be available on a renewable basis to locations such as Tampa, New Orleans, and Brownsville. Installed U.S. electrical capacity is presently about three times that amount. Utilization of the ocean thermal resource in one location could constrain the potential resource available downstream, depending on how the thermal effluents are discharged. Similarly, recirculation of its own thermal effluents could have an adverse influence on the performance of a single OTEC power plant, since its power output is roughly proportional to the square of the available temperature difference. Accordingly, there is an economic incentive for operating OTEC power plants so as to cause minimal perturbation of their thermal environments.

The implementation of large numbers of OTEC power plants for commercial applications will require significant capital investment and the investment of large amounts of energy in materials and plant construction. However, from a net energy standpoint, the payback time (or "breeding time") for an OTEC plant seems favorable — about a year. From a global standpoint, OTEC represents a substantial potential increment in world energy supply. In particular, it could provide (see Figures 2A and 2B) tens of thousands of megawatts of electricity via submarine cable to many nations in tropical and subtropical regions in a band extending up to about 25 degrees in latitude on either side of the equator. In addition, OTEC plant-ships could supply electricity via electrical bridges and energy-intensive products to worldwide markets. In principle, much of the present electricity produced by the combustion of oil could be replaced by OTEC power. Each megawatt of baseload oil-derived electricity for which OTEC power is substituted is equivalent to about 40 barrels of oil per day that can be utilized for other applications. For example, in the case of an OTEC plant operating at a capacity factor of 0.8 whose electricity costs 4 cents per kilowatt hour, the cost of displacing a barrel of oil is about $30.

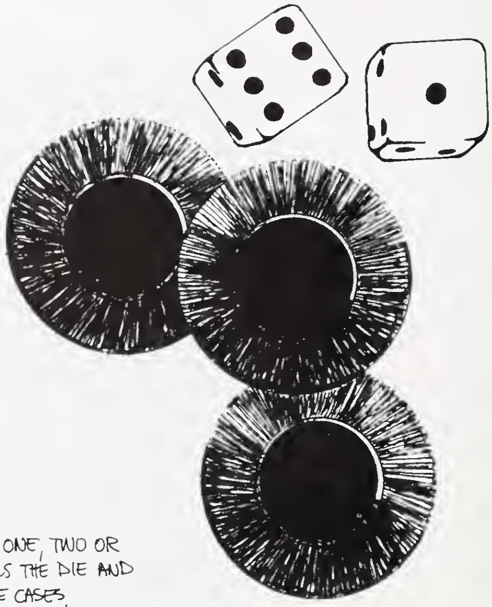
Because of the location of the world ocean thermal resource, it tends to be available to many islands and developing countries. The modular nature of OTEC plants — besides facilitating

RULES

THE IMPLEMENTATION OF ANY NEW ENERGY SOURCE IS FRAUGHT WITH TECHNICAL CHALLENGES, MANAGERIAL DILEMMAS AND POLITICAL CRISES.

OCEAN THERMAL ENERGY CONVERSION (OTEC) IS NO DIFFERENT.

ALTHOUGH THE TECHNOLOGY NEEDED TO BRING OTEC TO FRUITION IS NOT NEW, THERE ARE MANY ISSUES WHICH MUST BE RESOLVED TO MAKE IT A COST-EFFECTIVE, VALUED CONTRIBUTOR TO THE NATION'S --- AND ULTIMATELY, THE WORLD'S -- ENERGY MIX. THESE INCLUDE PLATFORM AND HEAT EXCHANGER CONSTRUCTION, MOORING, DELIVERY OF THE ELECTRICITY, OFF-SHORE POWER APPLICATIONS AND FINANCING.

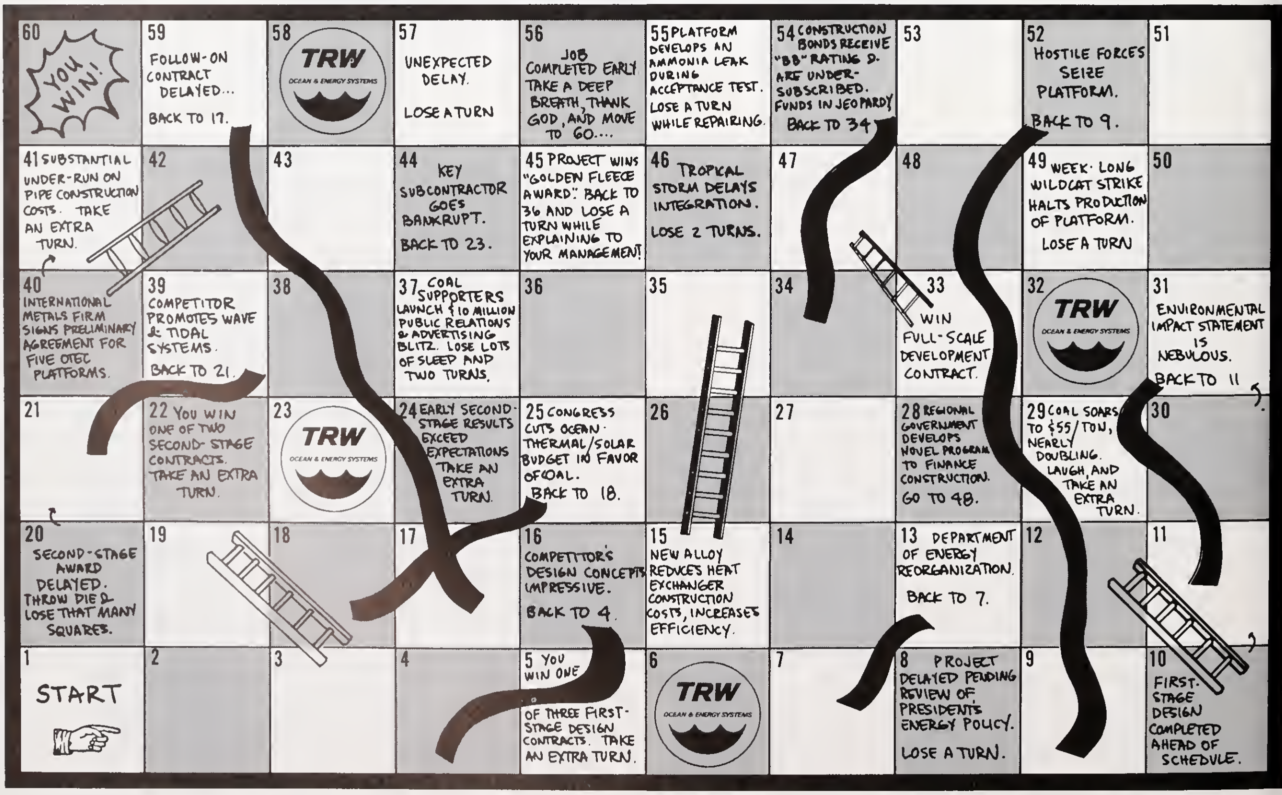


THE IDEA BEHIND THIS GAME, THEREFORE, IS TO PROVIDE YOU WITH A HUMOROUS, BUT SOMEWHAT ACCURATE, GLIMPSE AT WHAT CAN HAPPEN AND THE PITFALLS A DEVELOPER CAN STUMBLE INTO, SOMETIMES THROUGH NO FAULT OF ITS OWN.

"PLATFORM TO SUCCESS"--THE OTEC GAME" CAN BE PLAYED BY ONE, TWO OR THREE PLAYERS. BEGINNING ON SQUARE 1, EACH PLAYER ROLLS THE DIE AND ADVANCES FORWARD THE NUMBER OF SQUARES SHOWN. IN SOME CASES, FORTUITOUS CIRCUMSTANCES OR CAREFUL MANAGEMENT WILL ALLOW YOU TO ADVANCE EVEN FURTHER. IN OTHERS, YOU WILL LOSE TURNS OR SLIDE BACKWARDS, DEPENDING UPON WHAT HAS OCCURRED.

GOOD LUCK AND HAVE FUN! WE HOPE THAT YOU WILL JOIN TRW AND OTHERS IN OUR ENDEAVORS TO DEVELOP OTEC INTO A VIABLE ENERGY SOURCE TO SERVE THE NEEDS OF THIS COUNTRY.

THE OTEC GAME: PLATFORM TO SUCCESS



OTEC game, put out by TRW Ocean and Energy Systems, Redondo Beach, California, and circulated at the Sixth Annual OTEC Conference in Washington in June, 1979. It lent both a humorous and thought-provoking note to the proceedings.

standardization — allows their size to be adjusted to match commercial applications. It is likely that the range of sizes of commercial plants will extend from 10 MWe to about 500 MWe. Energy costs for plants up to about 100 MWe will exceed those of larger sizes; the limiting size of OTEC plants will probably be determined by the ability to construct their platforms cost-effectively. The provision of the OTEC option to the world energy market would add a new source of renewable energy having a substantial potential to help meet growing worldwide demands for additional energy. In a global climate where aspirations for energy are beginning to exceed the plateau in the supply of depletable energy reserves, OTEC-derived electricity and energy-intensive products could help reduce foreseeable polarizations among nations over energy resources.

The strategy of the United States OTEC development program is to demonstrate to industries and utilities the technical performance, reliability, and cost-effectiveness of OTEC systems. The introduction of commercial OTEC plants will probably require federal incentives, such as a combination of loan guarantees, low-interest loans, investment tax credits, cost-sharing, and other instruments. As additional units are deployed, system improvements resulting from experience are expected to lower their costs compared to initial units. Early units would be introduced in island markets by 1990, and into gulf states and international markets during the mid-1990s.

Many factors are involved in OTEC commercialization beyond questions of technical and economic viability. Financing of OTEC plants must be obtained; it is yet to be determined who will be the owners or operators. Candidates include consortia of industries, utilities, and shipowners; leverage-lease financing is another possibility. Thus centralized OTEC facilities might be subject to decentralized control. It is essential that each OTEC power plant be able to operate in a desirable location under a satisfactory legal regime.

Operation of OTEC power plants and ships in the economic zones of coastal states and in international waters will require bilateral and multilateral agreements among nations. Along with government incentives, there will probably be a need to avoid regulatory features that might discourage financial investments. The relative attractiveness of OTEC as an investment opportunity, in an era when the demand for capital will likely exceed its supply, will probably be a strong factor in determining market penetration, perhaps outweighing questions of cost-competitiveness.

Environmental Concerns

Finally, there are some important environmental concerns. The operation of an OTEC power plant will likely modify the thermal, biological, physical, and chemical properties of its environment. Thermal perturbations could affect the optimum performance of the plant. For example, recirculation of the warm or cold water effluents into the warm water intake could lower the temperature there, thereby reducing the plant's power output, and the reduction in ocean surface temperature could possibly affect local meteorology. However, appropriate discharge of the thermal effluents, as evidenced by experimental and analytical fluid-dynamical modeling, would limit surface temperature decreases to a small fraction of a degree Celsius. Other studies are being conducted to assess, understand, and minimize the possible environmental consequences of OTEC power plant operation. Impacts of the environment, such as sea state, on the design, siting, and operation of OTEC plants also are being considered.

Constraints on OTEC implementation could arise if too large a concentration of plants in a given geographical region degraded the available ocean thermal resource through effluent recirculation. For electricity-to-shore applications, where mooring of a plant will probably be required, sites would be limited to ocean regions with depths between about 1,000 to 2,000 meters.

Additional environmental concerns include impingement and entrainment of biota; possible discharges of biocides, corrosion products, and working fluids; artificial reef, nesting, and migration impacts; and worker safety. Research projects for investigating these concerns are

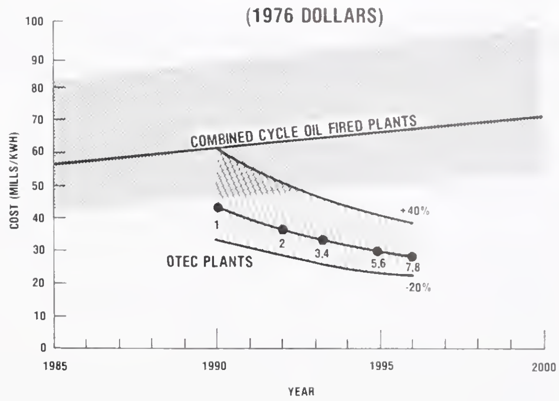


Figure 9. A comparison of post-1985 energy costs (based on 1976 dollars and public financing) for new power plants in Puerto Rico. Within the range of energy costs for electricity derived from new combined cycle oil-fired power plants (stipled band) is the most probable cost (solid line), assuming oil costs increase annually a few percent above inflation. The cost of the first 250 MWe OTEC power plant is estimated at $2,800 per kilowatt, followed by cost reductions for subsequent plants (numbered points).

summarized in the U.S. Department of Energy's OTEC Environmental Development Plan, 1979.

Environmental parameters likely to affect the design and operation of OTEC plants were catalogued by Charles L. Bretschneider in 1977 on a worldwide basis. This analysis considered sea state in general, including the effects of winds, waves, and surface currents. The ocean thermal resource can be disrupted by natural phenomena, such as coastal upwellings and hurricanes. For example, the formation of a hurricane can extract enough ocean thermal energy to reduce the thermal gradient by about 1 degree Celsius for several days. OTEC power plants must be designed to withstand hurricanes and heavy seas. However, oil-drilling platforms comparable to OTEC platforms are operating satisfactorily in the rugged North Sea environment.

Robert Cohen is a Program Manager in the Ocean Systems Branch in the Division of Central Solar Technology of the U.S. Department of Energy.

Note: The views expressed in this article are those of the author, and are not necessarily, in all or in part, those of the U.S. Department of Energy.

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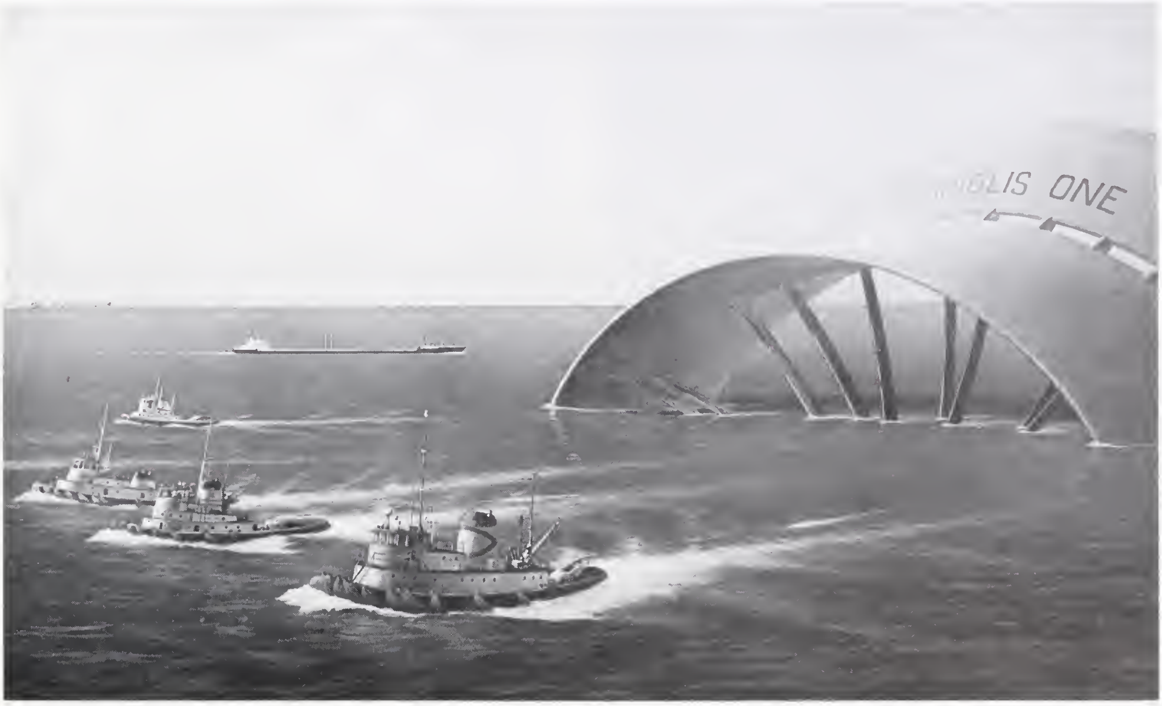
The Coriolis Program



Artist's conception of Coriolis prototype on tow to mooring station.

by P. B. S. Lissaman

The oceans are the major receptor of the sun's daily energy; they process, condition, and store this virtually limitless flux. Among the most powerful reservoirs of solar energy are the ocean gyres, or circulating current systems, generated by the prevailing global winds. The density of this current energy is quite high, being created by a twofold intensification of direct sunlight; first, by the transformation of the sun's heat into wind, then through the transfer by the surface wind stress into the wind-driven currents — all a part of the mighty global heat engine. In the Northern Hemisphere, the gyres rotate clockwise, and, because of the earth's spin, they are strongest on the western shores of the oceans. In 1835, Gaspard Gustave de Coriolis published a paper analyzing the distortions of fluid motions resulting from the earth's rotation. It is the Coriolis Effect* that intensifies the western portion of the North Atlantic gyre, the Gulf Stream system, effectively adding a third concentration to this natural energy flux. Thus the Florida Current, flowing only 30 kilometers due east of Miami Beach, contains 50 times more energy than all the rivers in the world. For many decades, visionaries and technologists have dreamed of using this power; now the problems of petroleum scarcity, escalating global energy demands, and political instabilities, coupled with large-scale engineering advances, have made this idea appear attainable.

The Coriolis concept was first proposed in 1973 by William J. Mouton, a civil engineer and Professor of Architecture at Tulane University in Louisiana. For Mouton, a former naval aviator and an expert sailplane pilot, the power of natural momentum fluxes is a continual obsession, both in his business as a designer of large structures and offshore rigs, and as a glider pilot. In 1973, standing on the levee in New Orleans, watching the roiling, turbulent flow of the flooded Mississippi, he, like

*A force acting on moving particles resulting from the earth's rotation. It causes moving particles to be deflected to the right of motion in the Northern Hemisphere and to the left in the Southern Hemisphere; the deflection is proportional to the speed and latitude of the moving particle.

Figure 1. Rotor/duct unit (1.5 meters) undergoing testing.

many before him, started thinking about the prospects of mounting hydro-turbines under platforms moored in the river. But Mouton is a man who does things on a large scale. One of his works was the American Sugar Dome in Charlestown, Massachusetts, a 59-meter diameter structure that was not only remarkably cost-effective but of sufficient aesthetic merit to be featured in the New York Museum of Modern Art's 1964 Exhibit of 20th-Century Engineering. The Mississippi seemed too small, too capricious. A few of the classic back-of-the-envelope calculations, and his mind turned eastward to the Gulf Stream, where a 150-meter machine, or many of them, could be installed in a current that was always in flood. Early in 1974, Mouton teamed with D. F. Thompson, president of TM Development, Chester, Pennsylvania. Thompson also is an individual obsessed with new ideas; his corporation presently manufactures the only certified lightweight advanced composite tuboprop aircraft propellers.

Thompson constructed the first small (1.0 and 1.5-meter diameter) rotor prototypes for the Coriolis program, which were tested alongside a powerboat (Figure 1). Together, Mouton and Thompson developed the first patentable ideas, then sought financial backing. This was provided in 1975 by Walter Hajduk, an industrialist of Pennsauken, New Jersey, who formed Hydro-Energy Associates to finance and direct the program. Three U.S. patents relative to Coriolis have been issued, and others are pending. Related patents also have been granted by 17 foreign countries, and applications are pending in 11 others.

A paramount concern of Mouton and Thompson was the environmental factor. The question was whether an array of ocean turbines would have any significant effect on the Gulf Stream current.

Early in 1977, Mouton contacted his old friend and gliding associate, Paul B. MacCready, president of AeroVironment, Inc. (AV), a California-based high-technology corporation that provides research and services in energy and the environment. MacCready discussed the fledgling Coriolis project with the author, a founding member of the corporation and principal hydrodynamicist, and Murray Gell-Mann, Professor of Physics at California Institute of Technology and winner of the Nobel Prize for Physics in 1969, also a founding director of AV.

The corporation specializes in energy and environmental studies, wind turbine development, and fluid dynamics. It designs and manufactures environmental monitoring instruments, including Acoustic Radar, which is being used at more than 200 sites in 20 countries. Another AV product line, AeroBoost, an aerodynamic fuel-saving device for trucks, designed by the author, is being manufactured in the United States and abroad. AV also has done advanced research in wind energy for the governments of Sweden and The Netherlands, the U.S. Department of Energy, the Solar Energy Research Institute, and the State of California. A continuing major effort has been in environmental impact prediction and research, where AV has worked with many major oil companies, utilities, and coal and uranium mining firms, as well as various government agencies.

At first, the Coriolis project, as outlined by MacCready to the author, sounded crazy, but on closer examination everything seemed sensible and logical. At the time, both of us were deeply involved with the development of the Gossamer Condor, the airplane that made history in August of 1977 by winning the Kremer Prize for the first human-powered flight. Although a far cry physically from the featherweight 34-kilogram Condor, the ocean turbine concept of Coriolis represented the same type of thinking — pushing technology to its rational limits. AV subsequently agreed to study the hydrodynamics of the concept, and its environmental implications.

The initial work focused on the dynamic effects of the Coriolis installation in the Gulf Stream flow. The calculations were based on the fundamental work done by Walter Munk of Scripps Institution of Oceanography in the 1950s on wind-driven ocean circulation. The essence of the method is to estimate the torque applied by the prevailing winds to the northern subtropical gyre, and to calculate the equilibrium speed of the current, assuming the main resistance to flow is provided by some effective turbulent viscous mechanism at the western periphery of the gyre. Then an additional resistance, corresponding to the drag of the Coriolis system, is applied and the new

equilibrium speed determined.

Several models were investigated, and the results showed that for an annual average extraction of 10,000 megawatts, the reduction in speed of the Gulf Stream is only about 1.2 percent, much less than its natural fluctuation. Further calculations indicated that any heating effects resulting from turbulence in the wake of the turbines would be very small. The actual heat/energy balance in the wake of a turbine involves quite subtle compensating factors, because although the turbine extracts energy (in kinetic form) from the flow, the wake reenergization by turbulent entrainment from the outer flow involves a dissipative heat-generating process. Theoretical calculations for an ideal energy-extracting device with wake velocity recovery resulting from entrainment indicate that the extra thermal content in the downstream section is about half the power extracted. Calculations indicate that the order of magnitude of the thermal effects is about 10^{-5} degrees Celsius.

Finally, the length scales for wake reenergization and the possible wave-making effects were studied. For the former, AV was able to use a computer model to estimate the reenergization of the wakes behind arrays of wind turbines. These calculations indicate that about 30 kilometers downstream of a cross-stream array, the wake perturbation will be indistinguishable from the general oceanic turbulence. Surface wave-making and internal waves were studied, with the consulting help of Russ Davis of Scripps, located at La Jolla, California. There did not appear to be any major problem; very conservative calculations indicate that the maximum perturbation near the units is on the order of 2 centimeters.

None of these findings is significantly adverse. It is evident, however, that the predictions should be confirmed by further study. A working group of independent oceanographers and marine engineers is being formed to study the issue. Of great importance to the feasibility of the project is the fact that any impact will accrue very gradually, since the installation will be staged over a 10-year period. A single turbine will have *less than 0.5 percent* of the effects previously listed. Thus the predictions can be validated when the effects of the earliest full-scale units first become measurable, and before any critical situation could occur.

Energy calculations indicate that an array of large turbines, each rated at 83 megawatts and about 170 meters in diameter could be moored in the Gulf Stream, in a relatively compact array of about 30 kilometers cross-stream dimension and 60 kilometers streamwise extent. The artist's rendering at the beginning of this article shows one of the first prototype units on tow out to its Gulf Stream mooring station. The system of 242 units could produce about 10,000 megawatts, a significant portion of Florida's electrical requirements, and the energy equivalent of about 130 million barrels of oil per year. Cost-effectiveness studies indicate that the units could be built and installed at a cost of about $1,200 per kilowatt. Thus the estimated total operating costs of Coriolis are very favorable. Including capital, operating, maintenance, and fuel costs, power is delivered at about 4.0 cents per kilowatt-hour, versus 5.6 cents for nuclear power and even more for coal and oil. These assume a plant factor of 57 percent for Coriolis, lower than what is reportedly typical of the other sources. The plant factor is computed in a way similar to that used for wind turbines, by considering the seasonal variation in the current, plus a two-week annual maintenance shutdown. Some comparisons are shown in Table 1. Thus the Coriolis system is an environmentally benign, cost-efficient method of extracting energy from a renewable source.

The engineering work carried out in 1974-77 involved detailed hull design, cost estimates, and feasibility checks with shipyards, as well as water testing of 1- and 1.5-meter power-producing models of the duct/rotor units. The work in the first phase established the engineering feasibility of the concept, determined that economically attractive power production is possible, and indicated that the environmental effects would be very small. These efforts have cost about $750,000, provided by Hydro-Energy Associates, with AeroVironment and Mouton and Thompson also donating efforts to the program.

In September, 1978, the U.S. Department of Energy entered the program, awarding a contract to AeroVironment (with the organizations of Mouton and Thompson as subcontractors) to study technical issues connected to the hydrodynamics of the system. This work involved design, analysis, and water tests of a 1-meter diameter model at the David Taylor Model Basin in the U.S. Naval Ship Research and Development Center, Bethesda, Maryland, as well as a technical and cost study of the mooring and anchoring arrangements. Work under this contract was completed in June, 1979. To date, results look extremely promising and largely confirm the original cost estimates.

The mechanical and hydrodynamic engineering of a turbine unit is interesting and original. Figure 2 shows a typical layout of the unit. The turbines are housed in a flared axisymmetric duct — providing one more amplification of the energy captured per unit area. Recent analytical and experimental work by the Grumman AeroSpace Corporation has demonstrated that similar ducts can be added to wind turbines, amplifying by two to three times the energy output of a free turbine. A detailed cross section of the turbine is shown in Figure 3.

The central mechanism of the Coriolis system is a two-stage rotor, consisting of a pair of

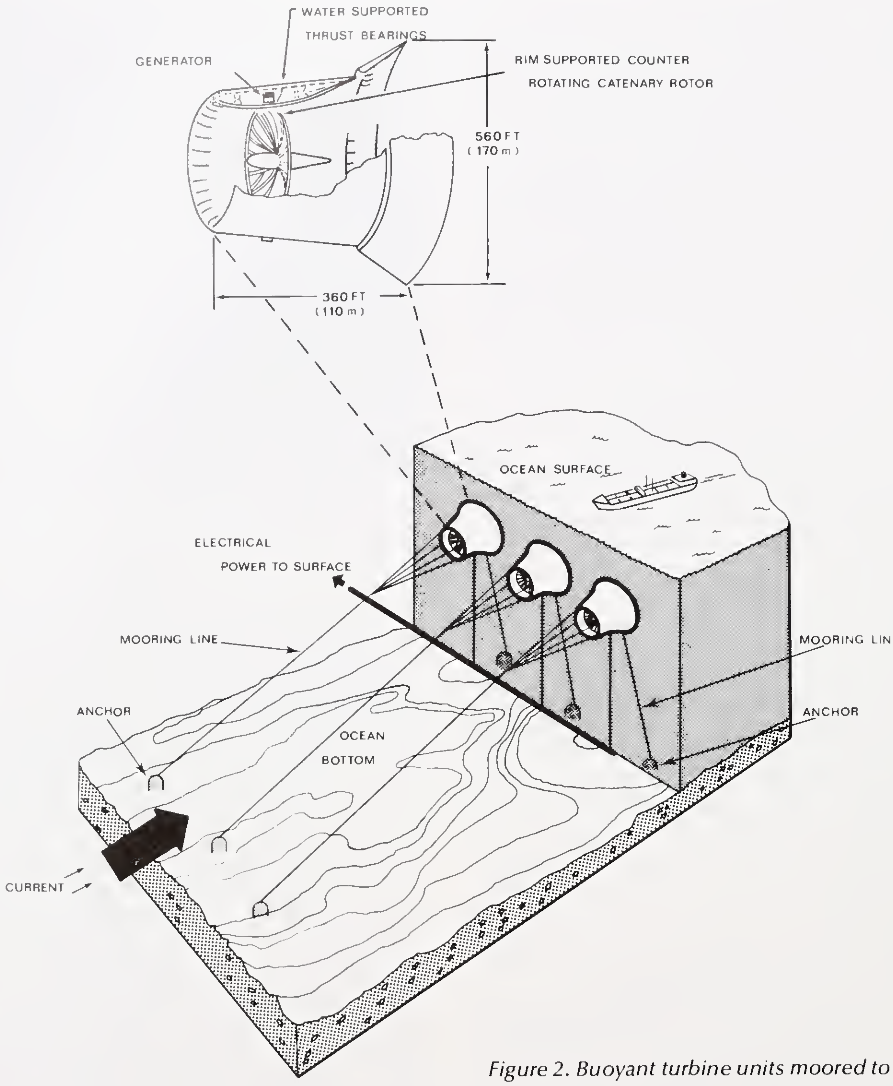


Figure 2. Buoyant turbine units moored to ocean bottom.

counter-rotating turbines, driven by the ocean currents in much the same way as the wind turns a windmill. Instead of being mounted on a conventional central shaft, however, the turbine blade tips are attached to circular rims. These rims drive electrical generators mounted inside the hollow cylindrical duct that houses the rotor.

This rim-drive/duct configuration affords several advantages. It makes feasible the large 91-meter rotor, which is necessary for economical power. Cantilever blades would be impractical, because of the massive loads. In the Coriolis configuration, the required strength is provided by a patented catenary blade construction. The flared, slotted duct augments the power significantly above that available from a free rotor of the same size, serving also as a housing for electrical and control equipment, and providing buoyancy for mooring, towing the system to site, and surfacing for maintenance.

Power is transmitted via high-voltage DC submarine cables and is inverted at the shore station. It thus is compatible with existing AC mainline power. Each unit has a rated power output of 83 megawatts, with 75 of these delivered onshore. The plant factor, which allows for current fluctuations and maintenance downtime as well as other items, is estimated at 57 percent. Thus one Coriolis unit delivers an average of 43 megawatts, comparable to the output of a small coal-fired station. The turbines are grouped in arrays, called pods, to facilitate mooring and maintenance. A small number of units can provide a significant energy source for a city the size of Miami Beach, and it also is quite feasible to deploy a large number in an oceanic energy farm. For example, 22 pods, each

Table 1. Cost comparison for new power in the United States (estimated 1978).

Plant	Plant Cost with Transmission (1978) $/kW	Plant Factor %	Fuel Cost (1978) ¢/kWh	Bus Bar Power Cost (1978) ¢/kWh
Combined cycle with oil*	535	65	6.0	8.3
Coal plus cleanup	1,035	65	2.1	7.3
Nuclear	1,330	70	0.7	5.6
Coriolis	1,050	57	0	4.0

Note: New utilities' power cost estimated by Southern California Edison Company (1978). Coriolis program power cost estimate by AeroVironment, Inc., and W. J. Mouton, Jr., C. E. (1978).

***The most up-to-date and cost-effective of the proven technologies for oil-based power generation, comprised of an oil-fired gas turbine followed by a bottoming cycle, consisting of a boiler and steam-turbine generator.**

of 11 units, can be moored in a 60- x 30-kilometer seaway, and will deliver onshore an annual average of 10,000 megawatts, enough to supply 10 percent of the energy needs of the State of Florida. A promising location is 30 kilometers east of Miami.

The Road Ahead

The overall objective of the Coriolis program is to place many turbine units in operation in the Florida Current, generating large amounts of economical power for the United States, and thereby achieving commensurate commercial rewards. Although basic feasibility has been largely established, substantial and costly efforts lie ahead. The future technical program is planned in logical phases of accelerating expenditure and commitment, addressing the more critical issues in the less costly earlier periods (Table 2).

The next step, Phase III, will determine optimum size, identify suitable sites, and confirm engineering, economic, and environmental estimates. The primary output of this phase will be the design of an 11-meter test module, suited for testing the basic mechanical, electrical, and hydrodynamic performance in water, under realistic service conditions. Before final design definition, there will be tests of certain critical subsystems, to establish proper determination of duct contours, rotor geometry, and mechanical details of the rim drive.

Parallel to the next technical steps in the program, ongoing major commercial backing will

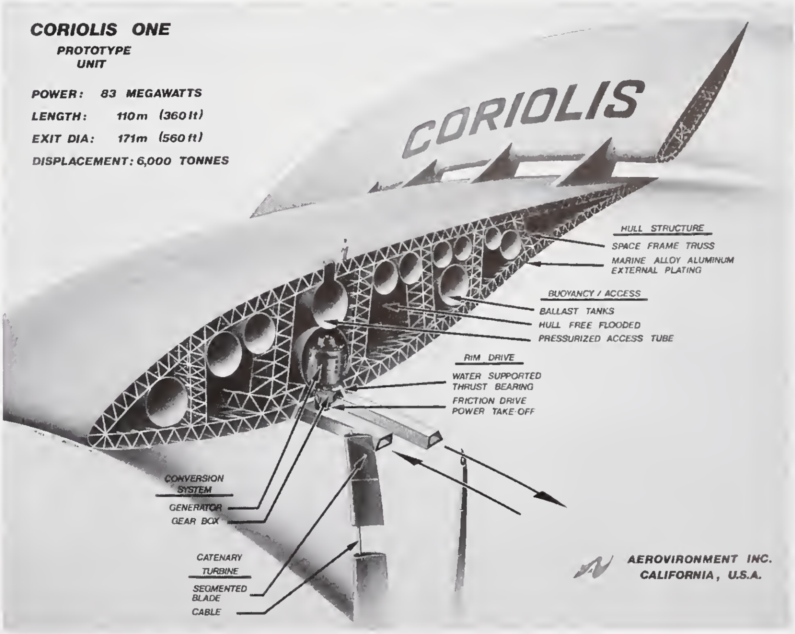


Figure 3. Cross-section detail of Coriolis unit.

Table 2. Summary of Coriolis program.

Phase	Objectives	Years	Date Complete	Est. Cost ($ Mil)
I	*Establish Feasibility* Environmental, technical, economic studies	4	1977	0.75
II	*Study Special Dynamic Effects* Hydroelastic, mooring, hull, additional environmental studies	0.6	1979	0.3
	TO DATE			
III	*Define Test Module* Plan 11-meter test module, test critical subsystems	0.8	1980	1
IV	*Sea Trials of Test Module* Design, fabricate, test 11-meter small-scale test module. Preliminary design of full size prototype	1.5	1981	4
V	*Sea Test Full-Scale Prototype* Design, fabricate, test 170-meter prototype unit to establish commercialization potential	3	1984	100

be sought. The energy needs of the country and the present program momentum call for an accelerated program. The country's economic interests can be served by Coriolis' potential effect on oil imports, by its effect in providing new jobs and stimulus to the U.S. shipbuilding industry (construction cost of each unit would be about $90 million), and also by its eventual status as an exportable, currency-earning energy technology. Such units, for example, would be of interest to Japan, where the Kuroshio Current could provide the energy.

These features appear to have created interest and backing in many places, including Congress. A number of senators and representatives have expressed support for the Coriolis program, and the latest Energy Appropriations Bill contains specific language directing the Department of Energy to fund further development of ocean current energy systems. Articles on the system have appeared in many periodicals and journals in the United States and abroad.

Throughout the program, environmental and economic issues have been of paramount importance in the designers' philosophy. Usually this pair make uneasy bedfellows; however, here there appears to be a very happy marriage. AeroVironment's calculations indicate that the major effect of the installation could be a very small change in the speed of the Gulf Stream, which would appear to have no significant adverse effects. A group of independent oceanographers and marine engineers is also studying the issue. At this stage, it appears that the Gulf Stream, first charted by Benjamin Franklin and later described by Admiral Maury as a "mighty river in the ocean," *will* "just keep rollin' along."

The economics also would have brought joy to Ben's frugal soul. Estimates of the cost of the system, including onshore power transmission, have been made and checked with marine engineering experts and commercial shipyards. As stated previously, they are comparable to or less than those of conventional new power systems. Much work lies ahead, but the first steps have been taken. In Pasadena, hard by the Pacific Ocean and the Jet Propulsion Laboratory, where so many space program dreams were realized, plans are being developed to extract huge amounts of energy from an ocean on the other side of a continent.

P. B. S. Lissaman is Vice President of AeroVironment, Inc., Pasadena, California. He presently heads a group doing research in wind and ocean energy programs funded by the Department of Energy and the California Energy Commission. An Associate Fellow of the American Institute of Aeronautics and Astronautics, he helped design the Kremer Prize machine, the first manpowered vehicle to achieve sustained flight.

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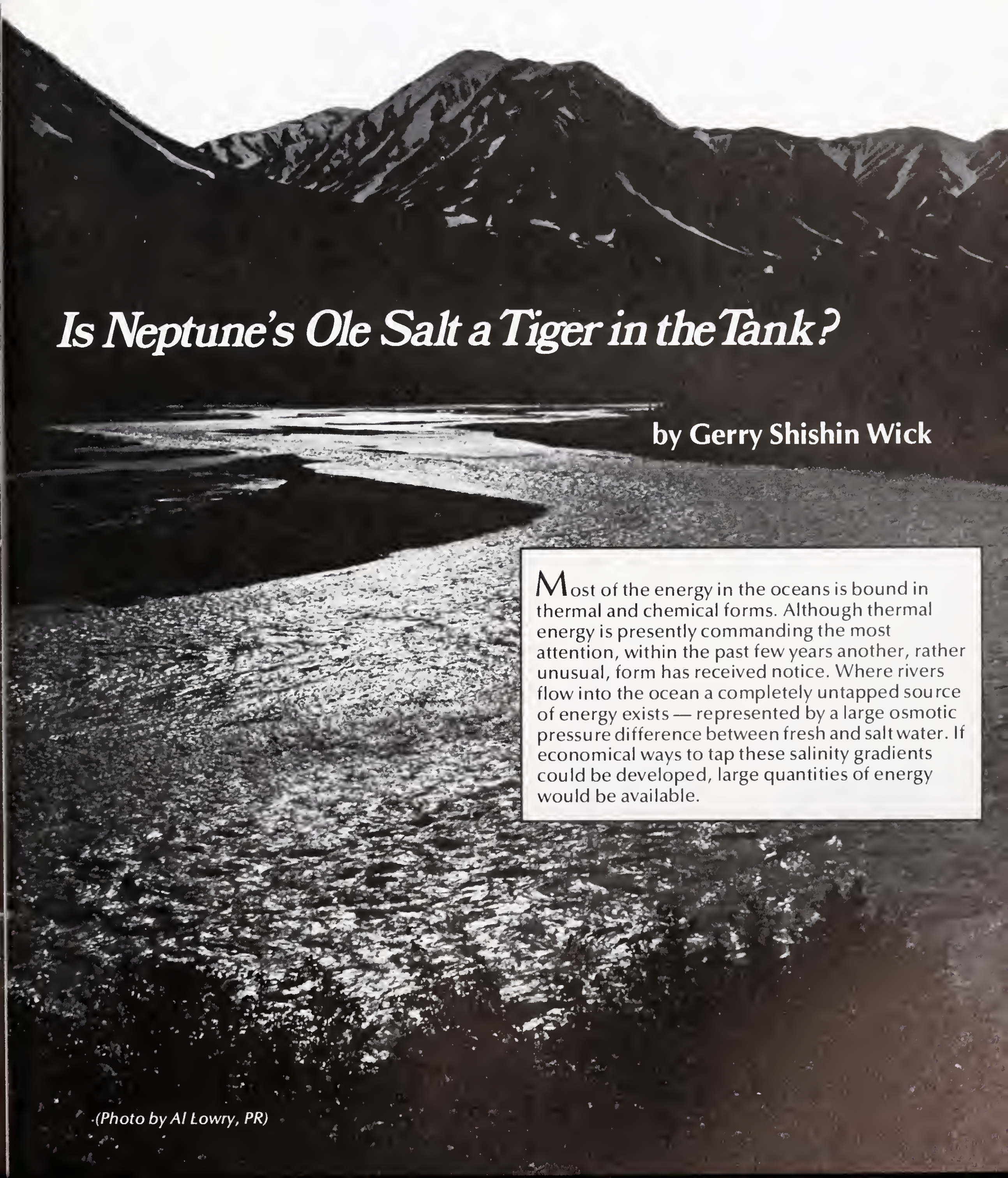
SALT POWER:

Is Neptune's Ole Salt a Tiger in the Tank?

by Gerry Shishin Wick



Most of the energy in the oceans is bound in thermal and chemical forms. Although thermal energy is presently commanding the most attention, within the past few years another, rather unusual, form has received notice. Where rivers flow into the ocean a completely untapped source of energy exists — represented by a large osmotic pressure difference between fresh and salt water. If economical ways to tap these salinity gradients could be developed, large quantities of energy would be available.

(Photo by Al Lowry, PR)

Because of the osmotic pressure difference, a 240-meter waterfall theoretically exists at the mouth of every river and stream in the world. Few dams are this high. At present, river water irreversibly mixes with ocean water with no social gain. However, if half of the flow of the Columbia River could be converted into electricity at only 30 percent efficiency, 2,300 megawatts would be produced. This is the size of two gigantic power plants.

Where the Jordan River empties into the Dead Sea, the energy density is even more spectacular. The nearly saturated brines of the Dead Sea have an osmotic pressure of about 500 atmospheres, corresponding to a dam more than 5,000 meters high! Every cubic meter of water flowing into the Dead Sea per second could theoretically generate more than 27 megawatts of power.

Table 1 shows the potential energy available from runoff of major rivers in the world and from other sources, including drainage into some hypersaline lakes. A value for global runoff also is given. This number represents the total renewable resource of salinity-gradient energy resulting from evaporation from the oceans, precipitation on land, and runoff back into the ocean. There are even larger sources of salinity-gradient energy, but some of them are nonrenewable. Nonetheless, the renewable salinity-gradient energy can make a dent in our energy budget.

How then, in principle, can we extract this energy that exists in salinity gradients? Consider this example: if a solution of fresh and a solution of salt water are separated by a semi-permeable membrane (a membrane that allows only water to pass, but not salt), the water would flow through the membrane from the fresh to the salt water side (Figure 1). This is not a new discovery. It was observed in ancient times, when wine was stored in sheeps' and pigs' bladders, and cooled in vats of water. The bladder, being a semi-permeable membrane, allowed the water to pass into it and dilute the wine. Sometimes the bladders swelled until they burst.

In our example, the fresh water would pass through the membrane and elevate the salt water until the pressure resulting from the height of the salt water is equal to the osmotic pressure difference. In the case of fresh and seawater, the osmotic pressure difference is equivalent to 24 atmospheres, or the pressure at the bottom of a column of water 240 meters high.

Figure 2 compares the renewable energy available from five ocean energy sources — ocean currents, tides, waves, and salinity and thermal gradients. It also shows the energy density of each source in terms of pressure head. Thus if one kilogram of water was acted on by the source, the number of joules generated would equal 10 times the pressure head. (The acceleration of gravity is 10 meters per second squared.) Salinity-gradient energy has the highest density, especially for brine, and ranks with thermal gradients as having the greatest power available. If all the salinity-gradient power from rivers were converted, it would supply

Table 1. Potential power resulting from salinity gradients. (From Wick, 1978)

Source	Flow Rate (m^3/s)	Osmotic Pressure Difference (atm)	Power (watts)
Global runoff	1.1×10^6	24	2.6×10^{12}
Amazon River *Brazil*	2×10^5	24	4.7×10^{11}
La Plata-Parana River *Argentina*	8×10^4	24	1.9×10^{11}
Congo River *Congo/Angola*	5.7×10^4	24	1.3×10^{11}
Yangtze River *China*	2.2×10^4	24	5.2×10^{10}
Ganges River *Bangladesh*	2×10^4	24	4.7×10^{10}
Mississippi River *USA*	1.8×10^4	24	4.2×10^{10}
Salt Lake *USA*	125	500	5.6×10^9
Dead Sea *Israel/Jordan*	38	500	1.8×10^9
USA waste water to ocean	500	22.5	1.1×10^9

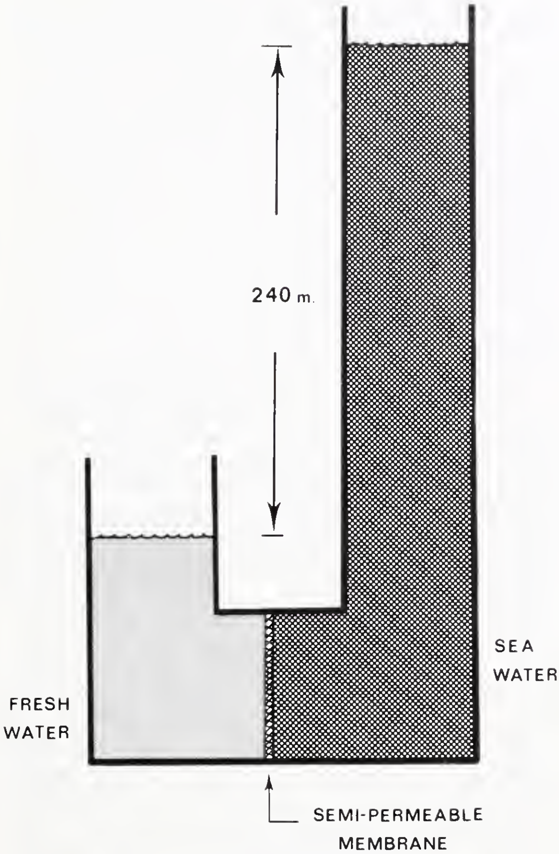


Figure 1. When separated by a semi-permeable membrane, the osmotic pressure difference between fresh and seawater maintains the latter at a height of 240 meters.

about 10 percent of the present global power demands.

By coincidence, the theoretical potential of hydroelectric energy from dams is approximately equal to that of salinity power from the global runoff of fresh water into the oceans. So, in principle, there is the possibility of extracting from river and stream flow at least as much energy as is extracted from hydroelectric dams. At present, hydroelectric energy provides a bit more than 10 percent of the electrical power utilized in the United States. There is little chance that this percentage will increase. Therefore, we cannot expect salinity-gradient power *from rivers* to provide a much greater percentage of the U.S. total. Nonetheless, it is not a trivial amount.

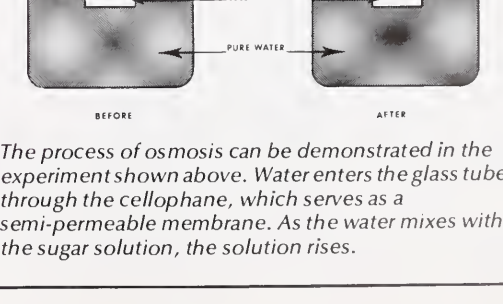
Tapping Salt Domes

There is another source of salinity-gradient energy — salt domes. These subterranean formations of brine or solid salt, located adjacent to or under the sea, contain a large amount of energy, perhaps even more significant than river runoff. The brine or salt dissolved from the domes could be pumped to the surface and interfaced with the seawater (or nearby ground water similarly pumped). Salt domes are of interest because they are likely sites for oil and natural gas deposits. Numerous formations have been monitored and drilled, particularly along the coastal zone of the Gulf of Mexico. These domes have yielded some of the largest oil strikes in the United States. Thus it is surprising that we may be able to convert greater amounts of energy from this salt supply than from the oil and gas.

To get an idea of the energy contained in salt domes, let us consider one of the several hundred salt domes in the northern Gulf of Mexico. A typical one would be about 1,600 meters (1 mile) wide, and 1,600 meters high. If the salt is dissolved to brine and the energy is converted at 100 percent efficiency, it would be sufficient to power a large power plant (1,000 megawatts) for 30 years. But considering inefficiencies, it might only be adequate for five years.

An extremely productive salt dome can yield 100 million barrels of oil, although the vast majority give much less. According to the Department of Energy, the domestic demand in the United States for all petroleum products is about 17 million barrels per day. Thus, if fully utilized, a huge field would run dry in a week. By comparison, the oil energy in a high-yield dome could power a 1,000-megawatt power plant for only 17 years — approximately half the salt value. Thus, even for a highly productive well, the salt is more energetic

How Osmosis Works



The process of osmosis can be demonstrated in the experiment shown above. Water enters the glass tube through the cellophane, which serves as a semi-permeable membrane. As the water mixes with the sugar solution, the solution rises.

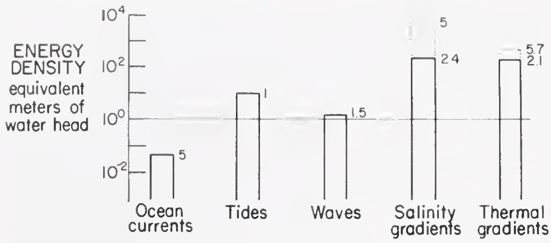


Figure 2a. Concentration of energy in different ocean sources expressed as meters of head. The ocean currents bar is velocity head. Salinity-gradients head is for fresh water/seawater, the dotted extension representing the head for fresh water/brine. For thermal gradients, the bar is for $\Delta T = 12°C$, the dotted extension for $\Delta T = 20°C$; the Carnot efficiency of about $\Delta T/300$ has been included.

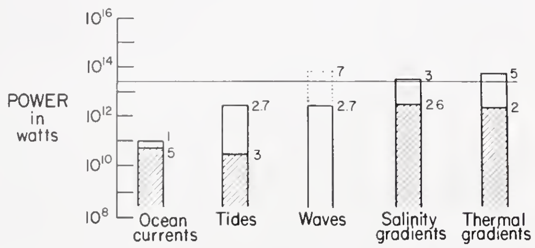


Figure 2b. Power or energy flux for various sources of ocean energy. The line at 15 TW (10^{12} watts) is a projected global electricity consumption for the year 2000. The dotted extension of the wave-power bar indicates that wind waves are regenerated as they are cropped. The salinity-gradient bar includes all gradients in the ocean; the concentrated gradients at river mouths, which will probably mainly be utilized, are indicated by the shaded area. Not shown is the power for subterranean salt or for river or seawater flowing into hypersaline ponds or salt flats, which undoubtedly would be large. The shading on the thermal-gradient bar indicates that portion of the power that is theoretically extractable in a Carnot cycle. On the ocean-current bar, the shading represents the power contained in concentrated currents, such as the Gulf Stream. Estimated feasible tidal power is shaded. (From Wick and Schmitt, 1977)

than oil in theory. This fact is clearly demonstrated in Table 2, which gives some actual examples. I have listed typical wells in three categories: high yield, medium yield, and low yield. There are many more wells in the low-yield category.

Furthermore, there have been more dry holes than strikes in the hundreds of salt domes that have been drilled. In fact, the majority contain no oil. Thus even if it could only be converted at 5 percent efficiency, this salt supply would be a large untapped energy resource. And recent research indicates that much higher efficiencies are possible.

Another likely source of salinity-gradient energy is the dried lagoons or salt pans along arid and semi-arid coasts. By controlling the influx of seawater into these lagoons, a concentrated brine can be maintained through solar evaporation. Then this brine can be interfaced with seawater, which would serve as the dilute solution.

Salinity-gradient energy is a form of solar energy and is continuously renewed in the case of rivers flowing into the ocean, or of inundated salt pans whose brine concentration is controlled by solar evaporation. The salt domes are examples of stored solar energy. They were formed in the geological past from evaporation of shallow seas. Thus they are nonrenewable on short geological time scales. As in the case of oil and gas, once the salt in such domes is mined and utilized, it is gone for eons.

The full extent of subterranean salt and its usable energy content is unknown. In the United States, there are immense salt deposits in the Mississippi Valley and under the Great Plains, as well as in other places. Figure 2 only gives the power available from river runoff. The power from salt deposits and from salt pans is undoubtedly much larger. But how do we convert this salt resource into usable energy?

Salinity-Gradient Energy Conversion

It takes energy to separate salt from water. Thus we might expect that the mixing of salt and water would release energy. Numerous methods have been developed to desalinate salt water. If they could be operated in reverse, many would yield energy. Only those methods that have a hope of commercial success will be reviewed here. The first such method is known as reverse electrodialysis, or the dialytic battery.

When two solutions of different salt concentration are separated by a "charged membrane," an electrical voltage is created between them. In the case of fresh water and seawater, this voltage is about 80 millivolts or 0.08 volts across one membrane. It is possible to stack 1,000 such cells in a series and generate 80 volts.

For a reverse electrodialysis stack, two types of charged membranes are used, called anion- and cation-permeable membranes. The cation-permeable membranes allow the positive ions (in this case mainly sodium ions, Na^+) to pass through, and the anion-permeable membranes allow the negative ions (mainly chloride ions, Cl^-) to pass through. If one alternately stacks anion-permeable and cation-permeable membranes, filling the alternate cells with fresh and salt water, respectively, the voltage adds up (Figure 3).

Electrodes are only needed at the ends of the stack. Under operating conditions, an anode of platinum-plated titanium and a cathode of steel waste 2 to 3 volts. With 1,000 membranes, the inefficiency caused by the electrodes is almost negligible.

Table 2. Comparison of the energy available from the salt and the oil in selected salt domes. (From Wick and Isaacs, *Science*, 1978)

Dome	Salt volume (cubic miles)	Oil production (10^3 barrels)	Salt energy (MW-years)	Oil energy (MW-years)
	High yield			
Thompson (Ft. Bend, Texas)	0.4	259,623	14,000	44,000
Hull (Liberty, Texas)	2.6	156,830	93,000	27,000
Humble (Harris, Texas)	9.8	138,639	350,000	24,000
	Medium yield			
Avery Island (Iberia, La.)	4.0	53,054	140,000	9,000
Bayou Blue (Iberville, La.)	4.6	20,806	161,000	3,500
Belle Isle (St. Mary, La.)	1.9	10,316	68,000	1,700
	Low yield			
Lake Hermitage (Plaquemines, La.)	0.9	2,475	32,000	420
Bethel (Anderson, Texas)	8.0	1,017	280,000	172
East Tyler (Smith, Texas)	4.3	55	150,000	9

In conventional electrodialysis, a voltage is applied across a stack similar to the one shown in Figure 3. In this mode, all of the cells would be filled with brackish water, and the end product would be fresh and salt water in alternate cells. Electrodialysis is used for many commercial processes, such as sweetening orange juice by removing some of the citric acid.

Some initial studies by John Weinstein and Frank Leitz at Ionics Corporation indicated that it would cost about $50,000 per kilowatt to build a reverse electrodialysis power plant. This figure is about 50 to 100 times greater than the capital cost of a conventional power plant. With thinner mass-produced membranes, it may be possible to reduce the capital cost to about $600 per kilowatt, becoming more competitive with other sources. Operating costs of about 2 to 4 cents per kilowatt-hour were estimated for reverse electrodialysis. This compares favorably with 2 to 4 cents per kilowatt-hour for power delivered to the local meter.

Research groups in the United States and in Sweden are further exploring the reverse electrodialysis concept. The biggest problem is the membranes. They are costly, subject to

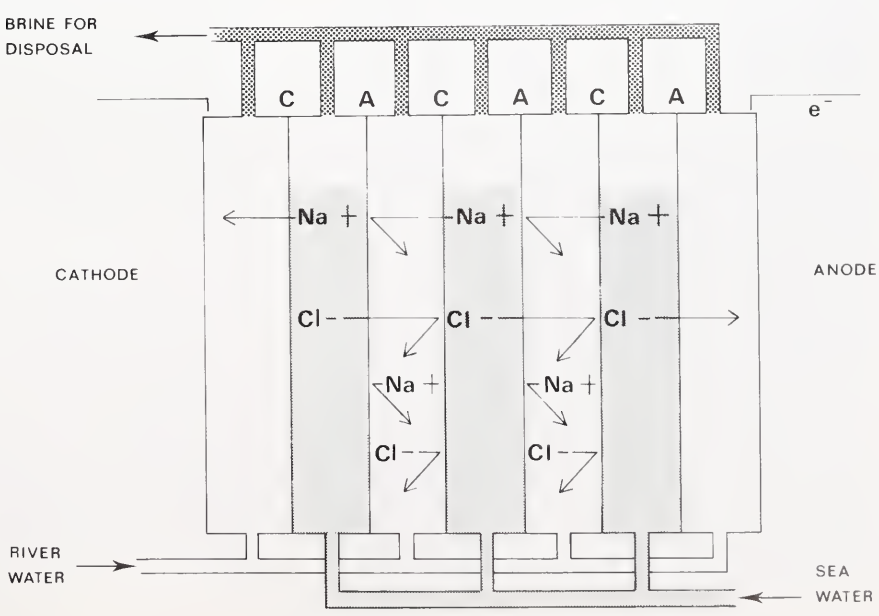
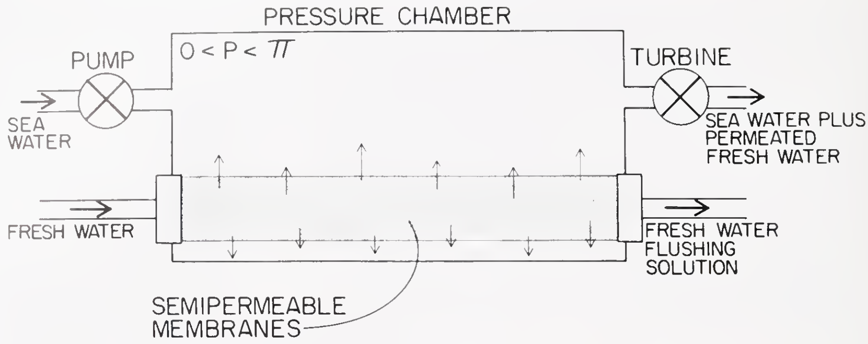


Figure 3. Reverse-electrodialysis stack. Only a few cells are shown here; many more would be included. The A and C refer to anion- and cation-permeable membranes, respectively. (From Wick, 1978)

Figure 4. A pressure-retarded osmosis energy-conversion device. The seawater is pumped to a pressure, P, which is less than the osmotic pressure difference, π. (From Wick, 1978)



degradation, and require pretreatment of the solutions.

Another method of energy conversion, which is subject to some of the same defects as reverse electrodialysis, is known as pressure-retarded osmosis. In 1975, Israeli researchers led by Sidney Loeb invented a device that directly utilizes osmotic pressure for power. Their method uses pumps, pressure chambers, and turbines to achieve the same effect as the 240-meter column of water cited at the beginning of this article.

High-salinity water is pumped to a hydraulic pressure equal to about half the osmotic pressure difference between the high-salinity water and the low-salinity water used in the device. The two fluids are separated by semi-permeable membranes, allowing the fresher water to flow into the more saline water. In order to permeate the salt water, the fresh water must flow against the pressure on the salt water side of the membrane. Essentially, the osmotic pressure drives the fresh water into the pressurized salt water (as long as this imposed pressure is not greater than the osmotic pressure difference). The power is generated when this permeated fresh water is released through a turbine (Figure 4).

Loeb's latest research, conducted in the United States, has allowed an estimate of the concept's economics. The calculations indicate that it would cost $10,000 per kilowatt to construct a plant, and 30 to 40 cents per kilowatt to deliver it to the user. Improvements in membranes could reduce the cost to 10 to 14 cents per kilowatt-hour, making it economically feasible. However, there are still some basic problems to overcome and more research to be done.

The two energy conversion ideas just described depend on membranes — semi-permeable for pressure-retarded osmosis and ion-selective for reverse electrodialysis. There are numerous technical difficulties with membranes, in addition to the high cost, deterioration, and solution pretreatment requirements mentioned previously. However, there is a promising method that requires no membranes.

Power can be extracted utilizing the vapor pressure difference between fresh (or low-salinity) and salt (or high-salinity) water. At the same temperature, water evaporates more readily from fresh water than it does from salt water. As a result of the lower vapor pressure on the salt water side, water vapor rapidly transfers from fresh water to salt water in an evacuated chamber. If a turbine is placed between the two solutions, power can be extracted. The corresponding desalination method is called vapor compression desalination. In reverse vapor compression, the vapor would expand through the turbines. The surfaces of the water act as membranes.

Because of the low vapor density and low pressure differentials, large turbines would be required to extract power. Similar ideas have been proposed for ocean thermal energy conversion or OTEC (see page 12). There is a comparable vapor pressure difference between cold deep ocean water and warm surface water. Modern designs incorporate 24-meter diameter turbine blades. The proposed ocean current turbines are even larger.

When the vapor transfers between the two solutions, it carries energy in the form of latent heat of vaporization. This is the heat that is released by the vapor to its surroundings when it condenses and absorbed from its surroundings when it evaporates. More energy is transferred by the latent heat of vaporization than is present in the vapor motion. This heat transfer would tend to slow down the process and eventually stop it unless the heat were returned to the freshwater reservoir or the system were flushed before much of the energy had been extracted. To overcome this problem, evaporation and condensation can take place on opposite sides of an efficient heat exchanger plate, as happens in vapor compression desalination. Figure 5 shows a model that graduate student Mark Olsson built at the University of California. It consisted of a spiral heat exchanger, doubling as a mixing pump when the unit was enclosed in a slowly

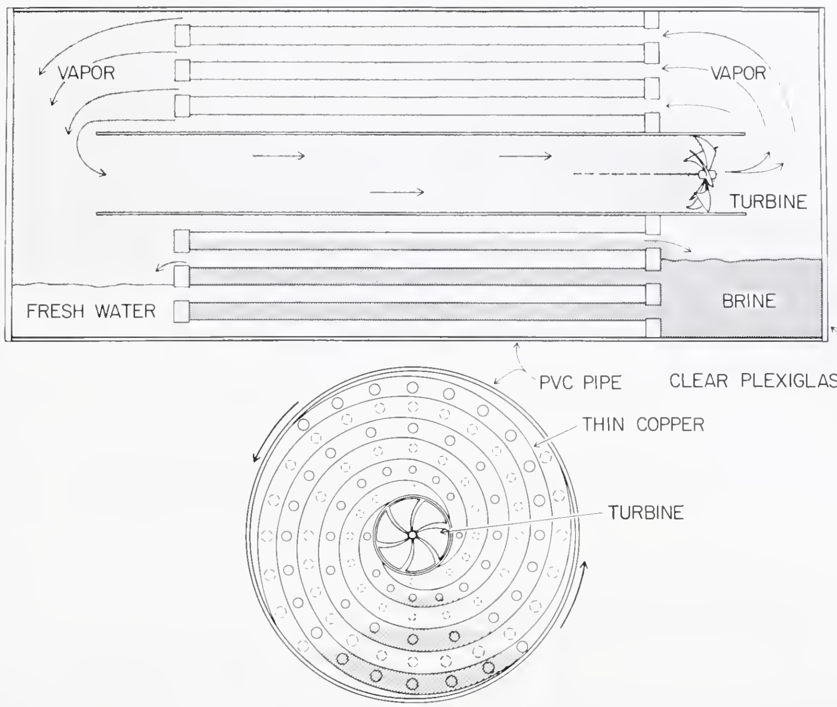


Figure 5. Double spiral pump for converting salinity gradient energy. Two views, end-on and cross-section, are shown. Rotation of the cylinder causes all the copper surfaces to be wetted by their respective solutions. As most of the evaporation and condensation occurs on these surfaces, latent heat is efficiently transferred. The turbine is driven by vapor transferring from the fresh water side to the brine side. (From Science, *1979)*

rotating cylinder. In tests, Olsson, John Isaacs, and I obtained power densities of as much as 10 watts per square meter of heat exchanger surface. This value is more than 10 times higher than for reverse electrodialysis. Furthermore, heat exchanger surfaces such as copper are much cheaper and longer-lived than membranes. Since water pretreatment is not necessary and biological fouling and corrosion are not so important, "reverse vapor compression" appears to be the most cost-attractive. Very high efficiencies, approaching 100 percent, are possible for low vapor transfer rates.

As the vapor pressure difference increases sharply with temperature, it would be advantageous to place a power unit near a low-grade source of heat, such as geothermal heat or waste heat from extant power plants. However, above 80 degrees Celsius, scale deposits may occur in some brines because of precipitation of gypsum. Another problem is maintaining a vacuum for rapid vapor transfer. Gases dissolved in the water need to be continually evacuated. This may not pose a serious problem, but needs to be considered in the overall operation.

Environmental Effects

The environmental impact of the development of salinity power at the mouths of rivers probably would be minimal except for the structures, some form of aqueduct, necessary to bring the two water bodies together in a relatively small space. In the mixing process, the amount of heat that is generated is trivial, raising the temperature less than half a degree Celsius, actually less than would result from natural mixing. The by-products would be discharged much in the same way as they are under natural circumstances. Thus it appears likely that deleterious environmental effects can be minimized.

Estuaries — among the most productive areas in the marine environment — are found at the mouths of many rivers. Any development concepts should be designed so that these vanishing areas are not put under further stress. Other important problems that need to be solved are the management of sediments carried by the rivers and the protection of marine animals that might be sucked into inlet pipes from the ocean.

Corrosion, biological fouling, and silting may

Ghor desert area of Dead Sea. (Photo by Hubertus Kanus, PR)

be very serious problems for the concepts that employ membranes. Some sort of filtration system will have to be developed for both the seawater and the river water. Pretreatment of the water may even be necessary to prevent fouling and corrosion, and also to increase the membranes' efficiency. There is some pretreatment now used in electrodialysis to minimize harmful effects. In the example of hypersaline sinks, the absence of organisms eliminates one of these problems. In concepts using vapor-pressure differences, fouling and corrosion do not appear to be serious problems. Fouling may not even occur in the evacuated chambers required for these methods.

The environmental effects from brines interfaced with seawater or fresh water depend on the location. Using lagoons along desert coasts, the end-product could be safely discharged into the ocean since it originated there.

Brines derived from salt deposits are somewhat different. They are not renewable and would represent an additional salt burden wherever they are discharged. In regions with continuous ocean currents, the resulting dilution of brine discharge would hardly be felt. However, other products, such as oil remnants, may need to be removed. Injection or reinjection of waste products into the earth has been suggested. The geological structure would need to be examined to insure isolation. Also, the expense might prohibit this form of disposal.

Future Prospects

Salt resources are clearly abundant worldwide, but certain conditions must be met in order to utilize salt for energy. The most important condition is the proximity of a large body of fresh water: this requirement is quite restrictive. Sunshine is needed to renew the salt resource and precipitation is required for the fresh water. Generally speaking, these two conditions do not occur in the same region.

If membranes could be developed to use saline water as the "fresh water" and brine as the concentrated solution, many regions would open up for salinity-gradient energy. Reverse vapor compression might be a more obvious approach. Significant portions of the United States have saline ground water. The salt domes in the Gulf of Mexico also can be used with seawater as the dilute solution. Similar situations exist in other countries.

Possibly, membranes suitable for use with

brines already exist. The Japanese have a problem of limited salt resources rather than limited fresh water resources. Thus in their electrodialysis units, they highly concentrate the brine and discharge the fresh water. Membranes have been developed to tolerate highly concentrated salt solution. It may be advantageous for salinity-gradient researchers to examine these membranes. Some preliminary work in this area has been done by Kurt Spiegler at the University of California.

By all indications, it is certainly possible to produce power from salinity gradients. We have seen that cost could be the most critical factor. We need an improvement of at least a factor of 100 in the cost of membranes before these concepts, such as reverse electrodialysis, would be worth pursuing.

One area that needs considerable investigation is a comparison of thermodynamic efficiency with economic efficiency. It appears likely that by operating at a very low thermodynamical efficiency some of the problems that require expensive components could be overcome. For example, the most efficient, most expensive membranes may not be needed where there is an abundance of water and consequently of potential power. In the employment of nonrenewable fossil fuels, early development capitalized on abundance and low efficiency. With salinity-gradient power, a renewable resource, such an approach might be more justifiable.

Also, the scale of the project must be considered. Small conversion plants could serve the nation's purposes better than large plants. The location of the plant, of course, would bear on its size. In remote regions without electricity, the salinity power of streams or salt pans could provide electrical power. Immediate applications also could be found for salinity power from brine, where the power density is much larger than for seawater.

It is not necessary to put all the nation's energy eggs in one or even two baskets. If an alternative energy source can provide even a few percent of the country's energy demands, then it is worth pursuing. Initially, ocean energy may make the best sense in select locations and in small-scale application. It is improbable that ocean sources will single-handedly solve the massive energy appetites of the globe. But as we gain experience, I would not be surprised if ocean sources make their mark by the turn of the century.

Gerry Shishin Wick is Director of the Institute for Transcultural Studies, Los Angeles, California. His research interests span a wide range of subjects, including nuclear physics, elementary particles, marine energy sources, deep scattering layers, tornadoes, and particle/turbulence interactions.

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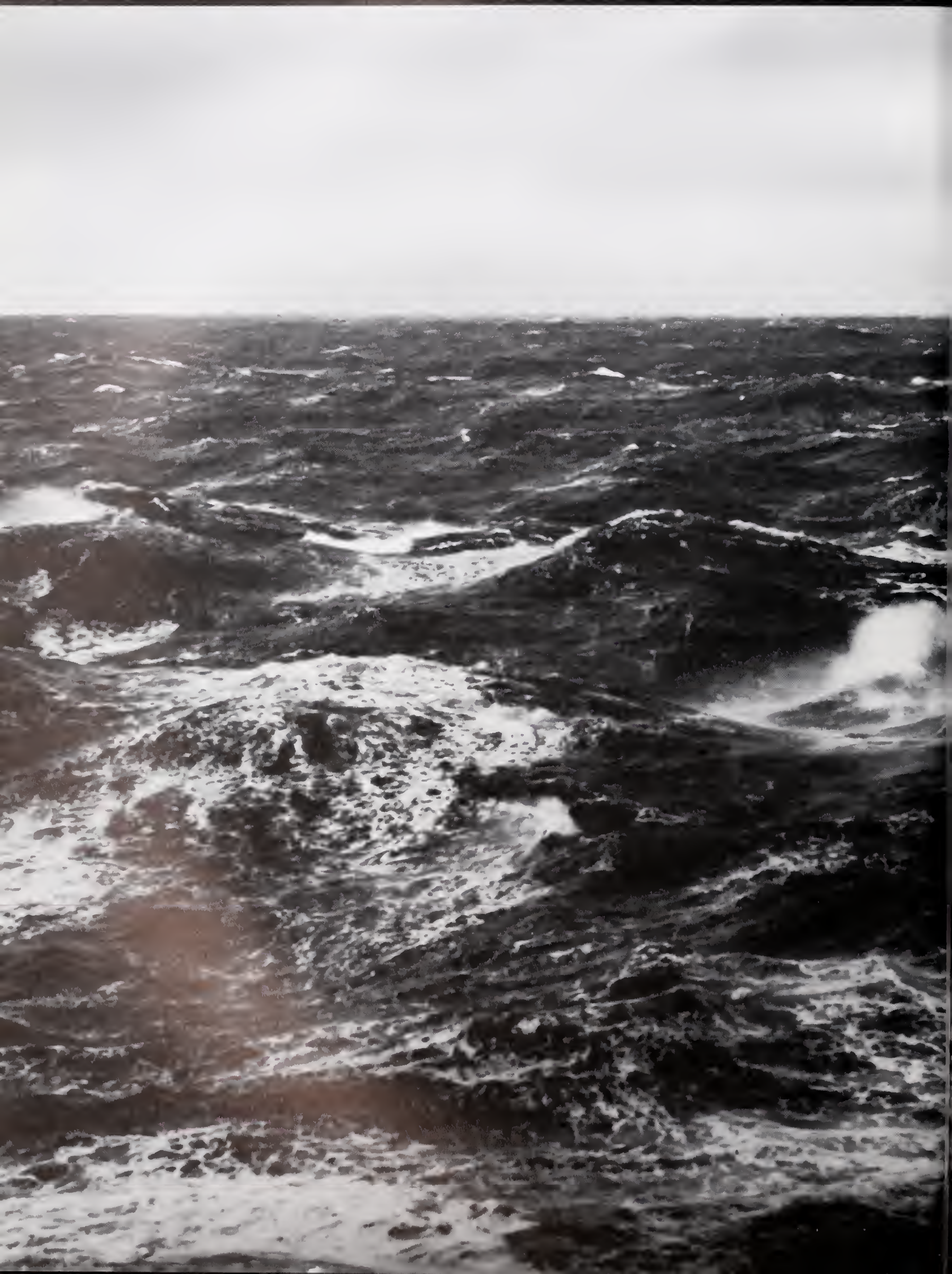
Power from



Ocean Waves

by J. N. Newman

Waves on the ocean surface are generated by atmospheric winds, acting over large areas and long periods of time. The resulting wave energy is effectively conserved until it reaches coastal waters, where the dissipative processes of bottom friction and breaking take their toll. Wave energy is delivered to the coastlines of the world at a rate comparable to our global power consumption, but the hostile environment of the ocean has thwarted our efforts to utilize this renewable resource.

The concept of a wave-power converter is relatively simple. A floating vessel, such as a raft or small boat, may be connected to a vertical cable that passes over a sheave to a counterweight, the sheave being suspended from a stationary dock (Figure 1). Vertical motions of the vessel will cause a rotation of the sheave, which may be used to drive a small electric generator. Work is done by the vessel on the sheave at a rate equal to the product of the rotational velocity and torque. Part of this work is transformed to electrical power, and the remainder is converted to waste heat via the mechanical and electrical losses of the system. To balance the total rate of work in such a mechanism, wave energy must be transferred to the vessel from the water at a rate that cannot exceed the rate of energy flux in the wave system. The rate of energy flux is the wave power.

In this primitive example, both the floating vessel and the dock (or an alternative submerged foundation) must withstand large loads, especially in storm conditions. The linkage must operate reliably and, for optimal performance, a sophisticated control system is necessary to modulate the restraining force on the vessel. At best, only low-grade power is supplied, the product of large forces and small velocities that cannot be converted efficiently with a simple mechanical system.

An essential requirement of any wave-power device is relative motion between two or more elements, such as the floating vessel and the dock of our previous example. The dock can be replaced by a submerged structure, fixed on the ocean bottom, or by a taut mooring system. Alternatively, power can be extracted from the motion between floating elements that move independently; for example, by connecting two adjacent floating vessels with a hinge, extracting power from their relative rotation. In this situation, the fixed structure or taut mooring is replaced by a much simpler slack mooring system, which is required only to withstand the small mean drift forces acting on the device. From this standpoint, devices with two or more moving

(Photo by Gordon S. Smith, PR).

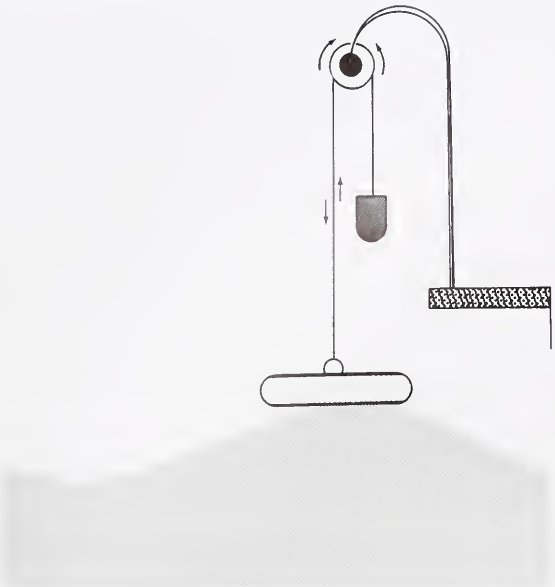


Figure 1. A simple wave-power device.

elements that are in equilibrium with the surrounding waves offer significant advantages over one that depends for its power output on a fixed frame of reference.

One or more of the moving elements in a slack-moored device may be internal. At a very low power level, navigational buoys with a bell or gong and bilge pumps that are actuated by the rolling motions of a small boat are examples of where use is made of the relative motions between the vessel itself and an internal mass. The internal device may be a moving fluid or air column, or a combination of the two, as in the case of a navigational whistle buoy.

At a more refined level, each of these alternatives has been the subject of research and development efforts carried out in the last several years, primarily in Japan, Britain, and Norway. Work in the United States has been devoted almost entirely to other sources of renewable energy; the development of wave power has been largely left to other nations.

Large-scale wave-power devices, both the vessel and the mooring system, are very expensive. Offshore plants for generating electricity have the additional cost of transmission ashore. Estimates for the cost of electricity generated in this manner, and delivered ashore, are about ten times that of electric power from conventional generating plants. However, these estimates are based largely on preliminary plans that are the products of intuitive design and limited experiments. Substantial improvements in performance are likely to result from a concerted development program, based on systematic experimental investigations and parallel theoretical analyses.

Estimates of Wave Energy and Power

Wave energy is distributed in a thin layer of the ocean, less than 100 meters in depth. (Our attention here is devoted to wind-generated surface waves, as opposed to less energetic internal waves.) The energy per unit of horizontal area is proportional to the wave period and to the square of the wave height. This energy is carried along at a reduced speed known as the group velocity, which in deep water is half the velocity of the individual wave crests. The product of the energy per unit area and the group velocity is the rate of energy flux per unit width of wave front.

It is essential to distinguish between the energy of ocean waves and its rate of transmission or power. Only the latter is relevant in the context of a renewable energy supply.

The total wave power incident upon the coastlines of the world has been estimated by various researchers to be between 2 and 3 times 10^{12} watts, a significant fraction of the world power consumption. From this viewpoint, wave power is a significant resource. There are, of course, substantial coastlines where wave power is of limited interest, and it is more appropriate to consider this subject on a regional basis.

Because of the prevalence of westerly winds, the most energetic wave climates occur on the eastern boundaries of ocean basins. The west coasts of Scotland and Norway have received the most attention as sources of wave power, but the west coast of North America is a comparable resource. Mean values of the incident wave power in these locations are between 10 and 100 kilowatts per meter of coastline. Peak values are on the order of one megawatt per meter.

Given this disparity between the mean and peak values of wave power, a logical approach is to design a conversion system for optimum performance at the mean level, which can be expected for a substantial portion of the year, subject to the requirement of survival in extreme conditions. Using the value of 10 kilowatts per meter, the wave energy flux along 100 kilometers of coastline has a potential yield of 1,000 megawatts, or the equivalent of one large nuclear or fossil-fuel generating plant.

Two-Dimensional Devices

The classical examples of ocean waves are two-dimensional, with identical form and motions at different positions along the wave crests. Such waves exist only in theory, or under laboratory conditions, but the more energetic ocean waves resemble this description sufficiently to warrant an initial analysis.

If the absorbing device is also two-dimensional, with its axis parallel to the wave crests, the interaction of the vessel and waves is independent of position along the device. The process of wave absorption is the same at each station along the axis, and the absorbed power is proportional to the total width of the device (which must be large, compared to the distance between successive crests).

The ideal hydrodynamic performance of a two-dimensional wave absorber can be explained most simply by noting the reciprocal role of a wavemaker. Within certain limits, any physically reasonable wave motion in the laboratory can be generated by a suitably designed wavemaker to which forced motions and power are applied by an external drive system. If a motion picture of this process is reversed, or if the wavemaker is "run backward in time," the waves appear to move toward the device and to be absorbed completely by its motions. Since wave motions are essentially a conservative process, this backward motion is in fact physically realizable and relevant. Moreover, it follows that an ideal two-dimensional device can absorb the incident wave completely, or with 100 percent efficiency.

Most laboratory wavemakers are situated at one end of the wave tank, with the objective of generating waves that move toward the opposite end in the offshore direction. The wave absorber that is strictly analogous would therefore be installed at the coastline itself. To avoid wave breaking and other complications, this arrangement is workable only if the coast is a submerged vertical cliff. A more useful device should function offshore, with the waves incident upon it primarily from one direction. For this reason, the geometry of efficient wave absorbers is identical to that of unidirectional wavemakers.

The simplest example of a unidirectional wavemaker is the wedge shown in Figure 2. If the wedge is driven in an oscillatory manner, in the direction parallel to the back side, the fluid disturbance will be confined essentially to the front. If the apex is sufficiently deep, the resulting waves will be trapped on the front side of the wedge, radiating away from this side in one direction.

The Salter cam shown in Figure 3 is an analogous form of a unidirectional wavemaker, but has the advantage of rotary motion. This particular configuration is the subject of an extensive effort at the University of Edinburgh, under the leadership of S. H. Salter. Early work with a single cam rotating about a fixed axis in a narrow tank demonstrated absorption efficiencies of 80 to 90 percent. In recent work, a moving axis of rotation has been used to simulate the performance with a slack mooring. An elaborate three-dimensional wave tank has been added to the facilities at Edinburgh to permit experiments with several interconnected cams in a more realistic seaway.

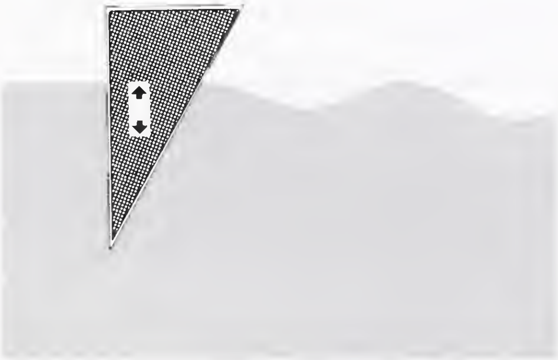


Figure 2. Unidirectional wedge-shaped wavemaker.

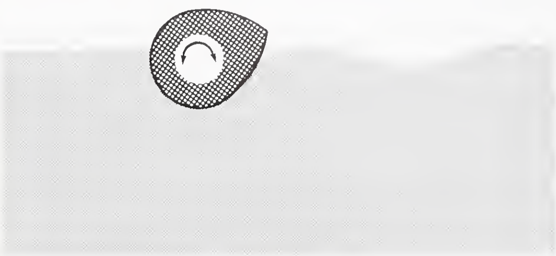


Figure 3. The Salter cam.

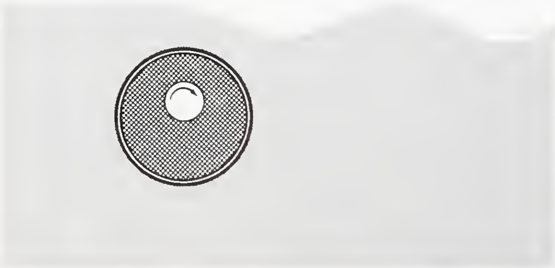


Figure 4. Unidirectional waves generated by orbital motion of a submerged cylinder.

Unidirectional waves may be generated alternatively by the forced oscillations of a submerged vessel. The corresponding wave absorber has possible advantages with respect to environmental impact and survival in storm conditions. An appropriate geometry for this purpose is a simple circular cylinder which, as shown in Figure 4, will generate unidirectional waves if it is given an orbital motion of circular form about its axis. Experiments to determine the feasibility of this scheme are being conducted by D. V. Evans and his colleagues at the University of Bristol in England, using pairs of taut moorings with

winch systems to impart the desired orbital motion to the cylinder.

Three-Dimensional Point Absorbers

A buoy or other vessel of small dimensions responds equally to waves from all possible directions. The same is also true of larger vessels of rotational form, with a vertical axis of rotation. This omnidirectional feature is advantageous if the incident wave energy is spread out directionally, but such a device has limited ability to capture the energy from long-crested waves. Theoretical models reveal that simple point absorbers can focus the incident wave energy from a capture width of about half a wavelength, if the power is absorbed simultaneously from vertical and horizontal motions. If vertical motions are used alone, the maximum capture width is one-sixth of a wavelength.

The fact that the maximum capture width is independent of the transverse dimensions of the absorbing device implies that a relatively small point absorber can be an attractive concept. It should be emphasized that the possibility of a capture width greater than the geometrical width of the vessel is in no sense contradictory to the laws of energy conservation. In fact, this is an example of wave "focusing" through a process of diffraction that is natural in three dimensions. An analogous result holds for a simple radio antenna, where the diameter of the wire or other elements is unimportant in relation to the power received or transmitted.

Small-scale point absorbers have been developed to a practical level through the pioneering work of Professor Yoshio Masuda in Japan. Four hundred units of 70 to 120 watts capacity have been in service for more than a decade as power sources for navigational buoys and lighthouses.

The development of point absorbers has been continued by Kjell Budal and Johannes Falnes at the Technical University of Trondheim, Norway. Parallel work has been initiated more recently at Chalmers University in Sweden, with application to possible use in the Baltic. Resonant tuning is used to amplify the vertical motions of the vessel, and power is extracted by a taut mooring or fixed structure.

Large arrays of these relatively small vessels are attractive from the standpoint of mass production and ease of deployment. The performance of the array in a monochromatic wave field can be enhanced by optimum spacing of the devices, but the narrow bandwidth of this tuning may be counterproductive in a realistic seaway.

Elongated Vessels

A three-dimensional wave absorber that is elongated in the direction perpendicular to the wave crests (as a ship is moored in head seas) offers the possibility of reduced mooring loads because of the relatively small projected width. If the oscillatory motions of the vessel are suitably modified along the length, for example, by joining shorter elements with hinges, power can be extracted from the relative motion between these subelements. This eliminates the requirement for a rigid foundation or taut mooring system.

The principal example of this configuration is the Cockerell raft (Figure 5). This device has been developed by a British industrial firm, Wavepower, Limited. Various models have been tested, including an intermediate scale vessel that was moored for an extended demonstration in the Solent, off Southampton. The Cockerell raft appears to have been designed in an empirical manner with limited experiments and no parallel analytical studies. No attempt has been made to promote focusing through optimum control of the motions along the length. The hinges between subelements are expensive, and their number has been reduced as the experiments have progressed. Recent work has been undertaken with a single hinge.

Recent theoretical work with an elongated

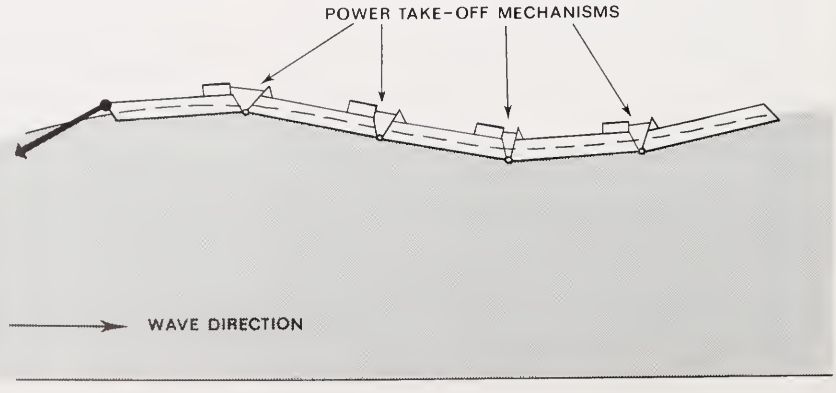


Figure 5. The Cockerell wave contouring raft.

set of rafts suggests that two hinges joining three rafts will give twice the power output of a single hinge. Capture widths comparable to the wavelength can be achieved with optimum control of the hinges.

Pneumatic Devices

From the standpoint of its effect on the surrounding wave field, an oscillatory pressure acting on the air/water interface is equivalent fundamentally to the motions of a floating or submerged vessel. This suggests the use of an oscillatory air column to extract power, in place of the vessel's motions or an internal device. Advantages of the oscillating air column are that its mass is small, and its motion can be amplified with a simple nozzle before passage through a small high-speed turbine. The resulting power is of a higher grade, with greater velocity and reduced force.

Various pneumatic wave absorbers have been proposed with geometric configurations and relative advantages that are similar to the oscillatory vessels just described. A few of the most interesting examples will be described here.

A two-dimensional stationary vessel with an internal air chamber has been proposed by the National Engineering Laboratory in Britain (Figure 6). The air within the chamber is in direct contact with an oscillatory water column, whose mass may be suitably chosen to promote resonant tuning with the incident waves. As a result of this resonance, and good hydrodynamic fairing of the submerged entrance to the water column, the internal air/water interface oscillates with greatly amplified motions relative to the external wave field. A feature of this device is a rectifying turbine of simple form that rotates in the same sense regardless of the air flow in or out of the air chamber from above. A similar submerged device with a second air/water interface is under development by the Vickers Corporation. Both of these appear to require a fixed foundation or taut mooring system.

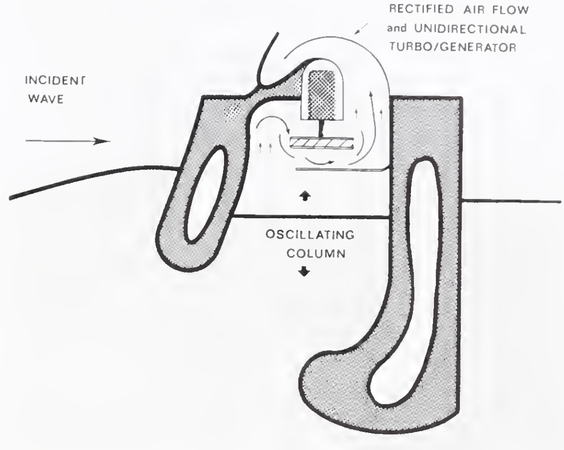


Figure 6. Advanced air bell of the type proposed by the National Engineering Laboratory in Britain.

Air chambers are arranged longitudinally in the interior of the Japanese *Kaimei* ship (Figure 7). This is a descendant of the Masuda navigational buoys, but with many separate chambers operated independently along the overall length of 80 meters.

Testing of *Kaimei* in the Sea of Japan has become an international project with joint participation from the United States, Canada, and Britain. Each country is responsible for its own tests in separate chambers, using different turbines. This project may result in interesting comparisons of the different turbines, but the absence of optimum control between the chambers suggests a relatively small capture width and power output.

Elongated vessels of this basic type combine the advantages of conventional ship construction, small mooring loads in the head-sea configuration, and conversion of the power with small high-speed turbines. Substantial improvement is likely to result from optimum control of the turbines and from

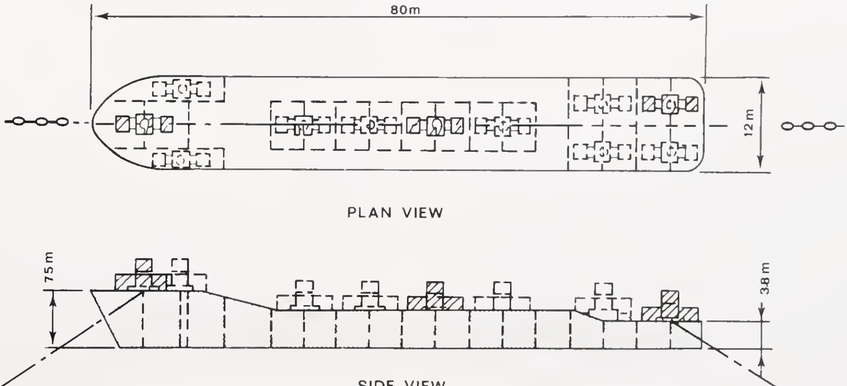
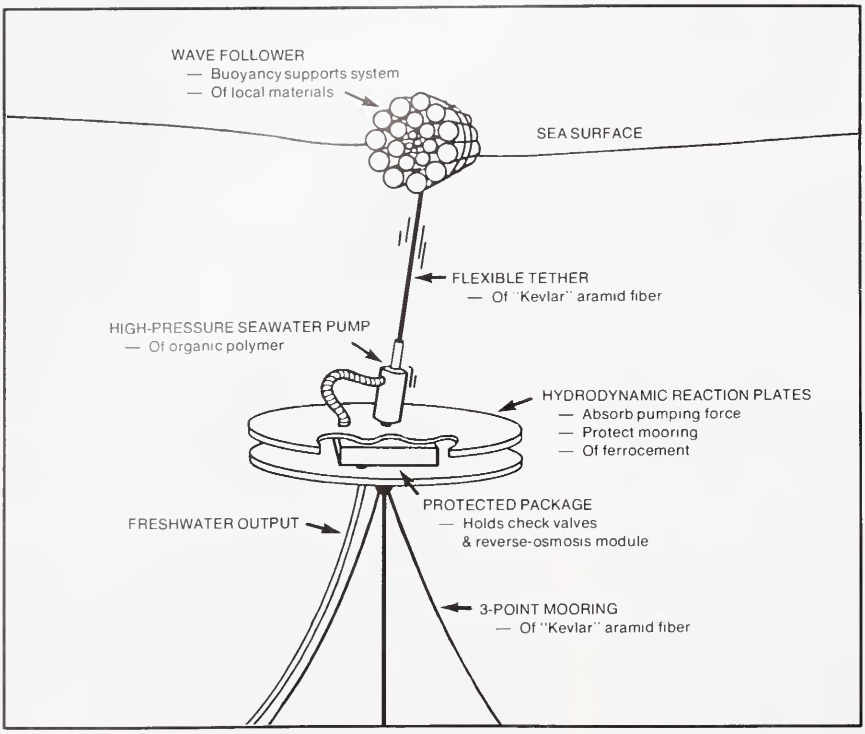


Figure 7. Masuda's 80-meter Kaimei *ship.*



Pump used in wave energy desalination device designed by C. M. Pleass at the University of Delaware.

greater attention to the locations and fairing of the submerged entrances to the chambers.

Stationary Collectors

Another category of wave-power devices is based on the use of a stationary structure to focus the waves and amplify the energy density prior to conversion of the associated power. Concepts have been proposed for this purpose in Norway and the United States, using submerged structures of variable depth to refract the waves or, in the simplest case, a horn-shaped collector with vertical walls. Care must be taken not to amplify the waves to the point where substantial breaking occurs. These devices also appear to suffer from the usual difficulties of building and maintaining a large fixed structure in the ocean.

Other Applications of Wave Power

The applications of wave power are not limited to large-scale electricity generation. As with ocean thermal energy conversion (OTEC), alternative utilizations may be more useful in the economic context of using energy offshore. If operation is feasible in mid-ocean, the available power can be increased by extracting wave energy at a sequence of locations downwind, spacing these sufficiently far apart to permit regeneration between stations.

Wave-power devices may be attractive on a small scale, on islands, and at other remote communities. One intriguing concept being pursued by C. M. Pleass at the University of Delaware seeks to employ small point absorbers for water desalinization. The wave energy is utilized to drive a high-pressure pump, passing seawater through a reverse-osmotic membrane. Preliminary work suggests an output of 1,000 liters per day, per meter of coastline.

Environmental Impact

The installation of large structures in close proximity to the coastline is not desirable from the standpoints of visual impact, navigation, and also possibly with regard to biological effects on the marine community. Moving offshore removes these objections to a degree. As with other sources of fuel for our enormous energy demands, the cost and benefits of wave power must be compared on a rational basis.

In common with other offshore structures, large wave-power devices may suffer infrequent catastrophe, notably if mooring failures lead to collision or grounding of the vessel. Since no large amounts of oil spill, gas leakage, or escaping radioactivity would be associated with such an event, the probability of its infrequent occurrence may be judged more acceptable than other possible catastrophes.

Another environmental concern is the effect on coastal processes that might result from a substantial decrease in the incident wave energy. The processes by which beach formation and other

littoral processes are affected by waves are not well understood. Even less is known about the direct or indirect effects of waves on marine life. Of course, the attenuation of ocean waves would be welcomed by many persons. However, wave-power devices will have little effect on the most undesirable storm waves, whose power exceeds the design level of the device by one or two orders of magnitude. The principal effect of successful wave-power devices will be to substantially reduce the more common and moderate waves that occur along the coast with greater frequency.

Future Prospects

Wave energy is an obvious source of power that has received substantial attention in recent years. Several devices have been conceived and tested on model scale, and a few concepts have been tested at sea. This is a fertile area for invention. Many concepts that appear to differ superficially are in fact fundamentally similar from the standpoint of hydrodynamic performance.

Relevant criteria from the design standpoint include not only the total power output, but also survival in the hostile environment of the ocean, and long-term operation with a high degree of reliability. Despite the efforts to date, an optimum or near-optimum solution to this design problem has not been attained; thus the estimated cost is not known for efficient conversion of wave energy.

Continued research and development in this field are likely to produce devices that are two or three times more efficient than those already conceived. If the cost of conventional power generation continues to escalate, wave energy conversion may become economic within the next decade, especially in regions where the wave climate is relatively energetic and the cost of conventional power is high.

J. N. Newman is a Professor of Naval Architecture in the Department of Ocean Engineering, Massachusetts Institute of Technology.

Acknowledgment
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Additional Readings

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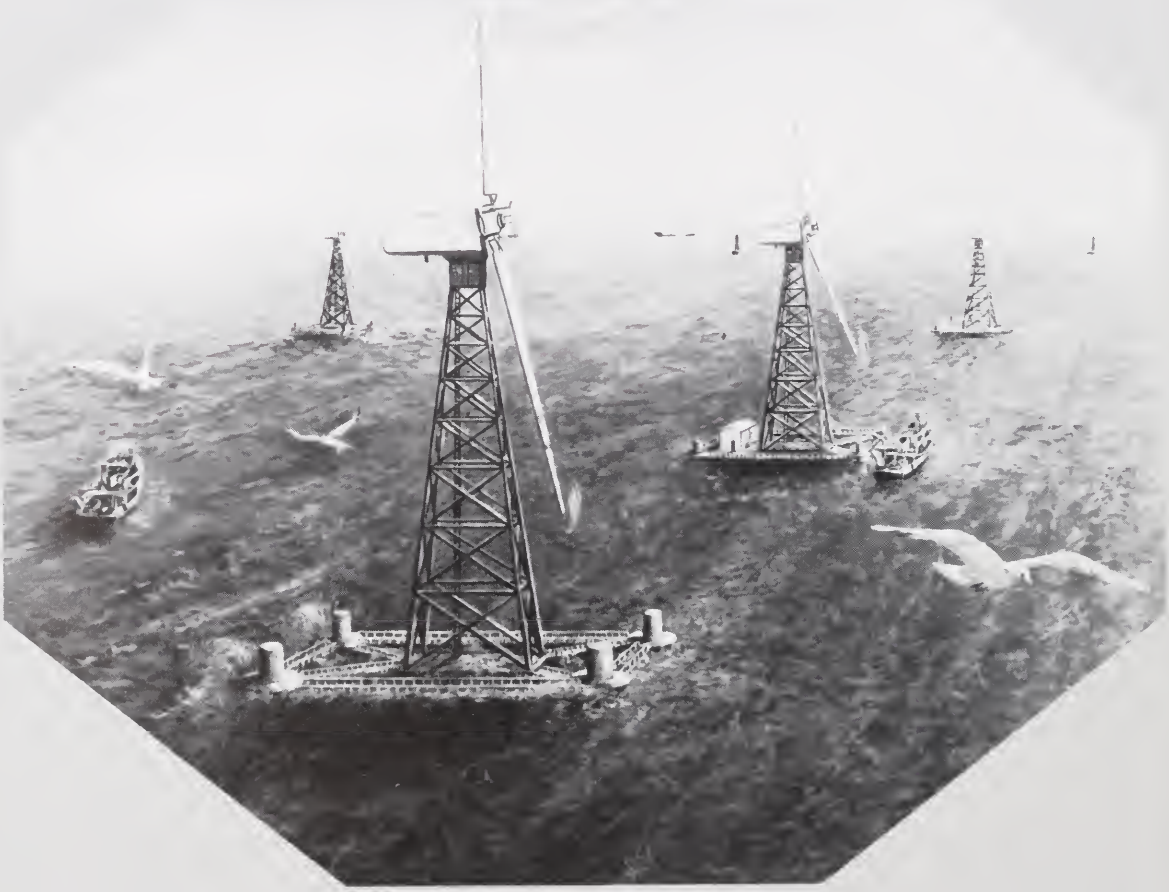
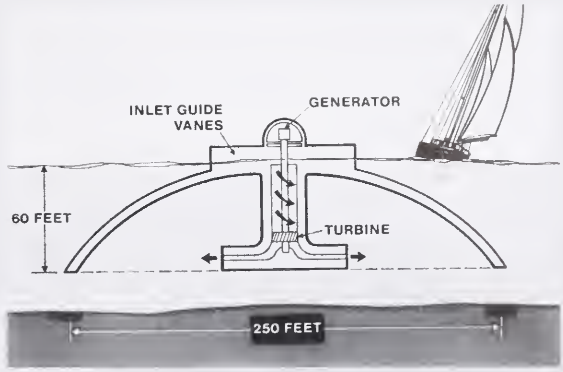
Offshore Wind Systems

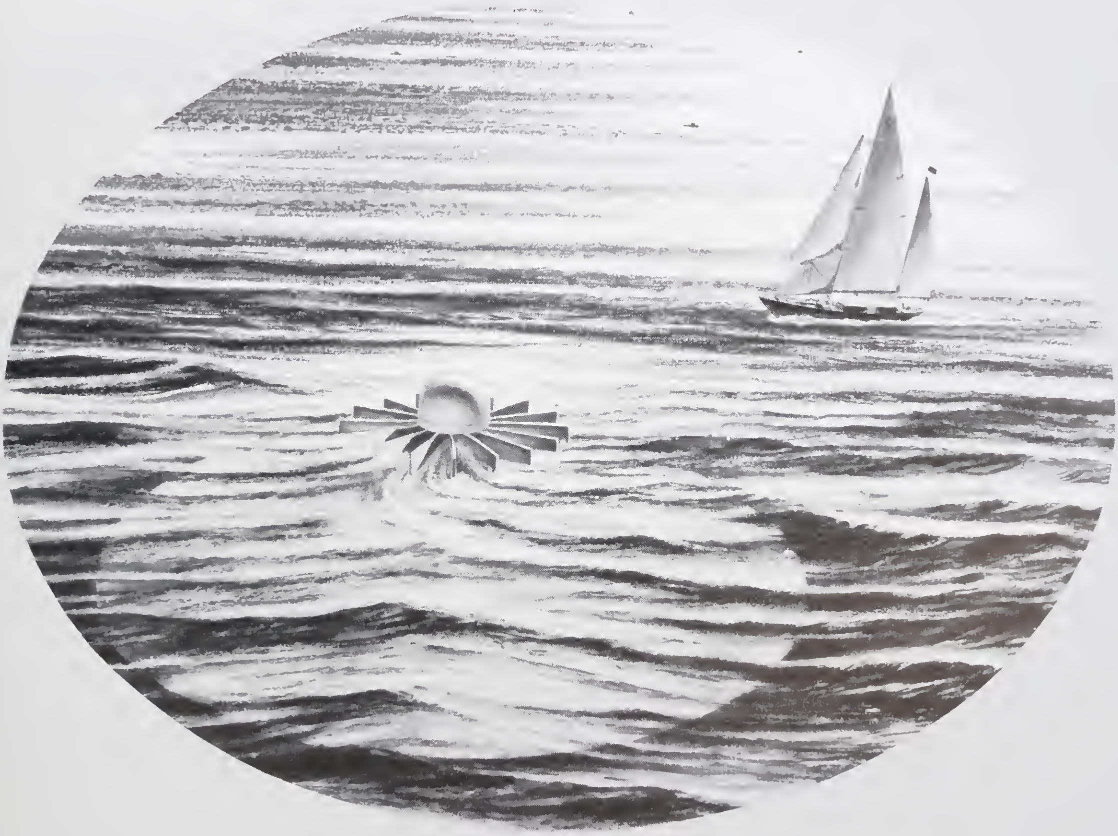


Offshore Wind Energy Conversion Systems (WECS) face problems similar to those which the oil industry had to face when it decided to go to sea. Towers for wind generators must arise either from the seabed or from floating stations, such as those visualized here by a Westinghouse artist. An underwater pipeline, or cable, or some other arrangement must be provided between the offshore resource and the onshore energy user. The size of the offshore wind resource is enormous (a 1972 National Science Foundation/National Aeronautics and Space Administration study reported that with maximum effort WECS at favorable sites along U.S. sea coasts and over the Great Lakes could be producing in excess of 1.3 billion kilowatt-hours of electricity annually by the year 2000). While many technical and economic problems remain to be solved in harnessing this energy, political problems could prove to be the most difficult to overcome. For example, the complex question of territorial waters is likely to be vital in any future implementation of offshore wind systems. At this time, the United States claims a 200-mile limit for fishing purposes only, while some coastal nations claim sovereignty out to 200 miles. The outcome of the question of national jurisdiction — presently being considered by the Third United Nations Conference on Law of the Sea — could strongly influence the scope of any future offshore wind program. Other social factors that will have to be addressed include recreational considerations, commercial fishing, shipping lanes, offshore drilling, environmental factors, and so forth. In Europe, Sweden and Norway have plans to establish offshore wind power facilities. The Norwegian program calls for 180 units offshore that will be arranged in 18 groups of 10 platforms each, generating 900 megawatts. Water depth at the platforms has been limited to 10 meters in an effort to keep construction costs down.

and a New Wave Energy Device



Lockheed's Dam-Atoll. Curved arrows in the central cylinder indicate the whirlpool action of the water in the central cylinder, which acts like a giant flywheel to keep the turbine spinning in spite of the intermittent wave action.

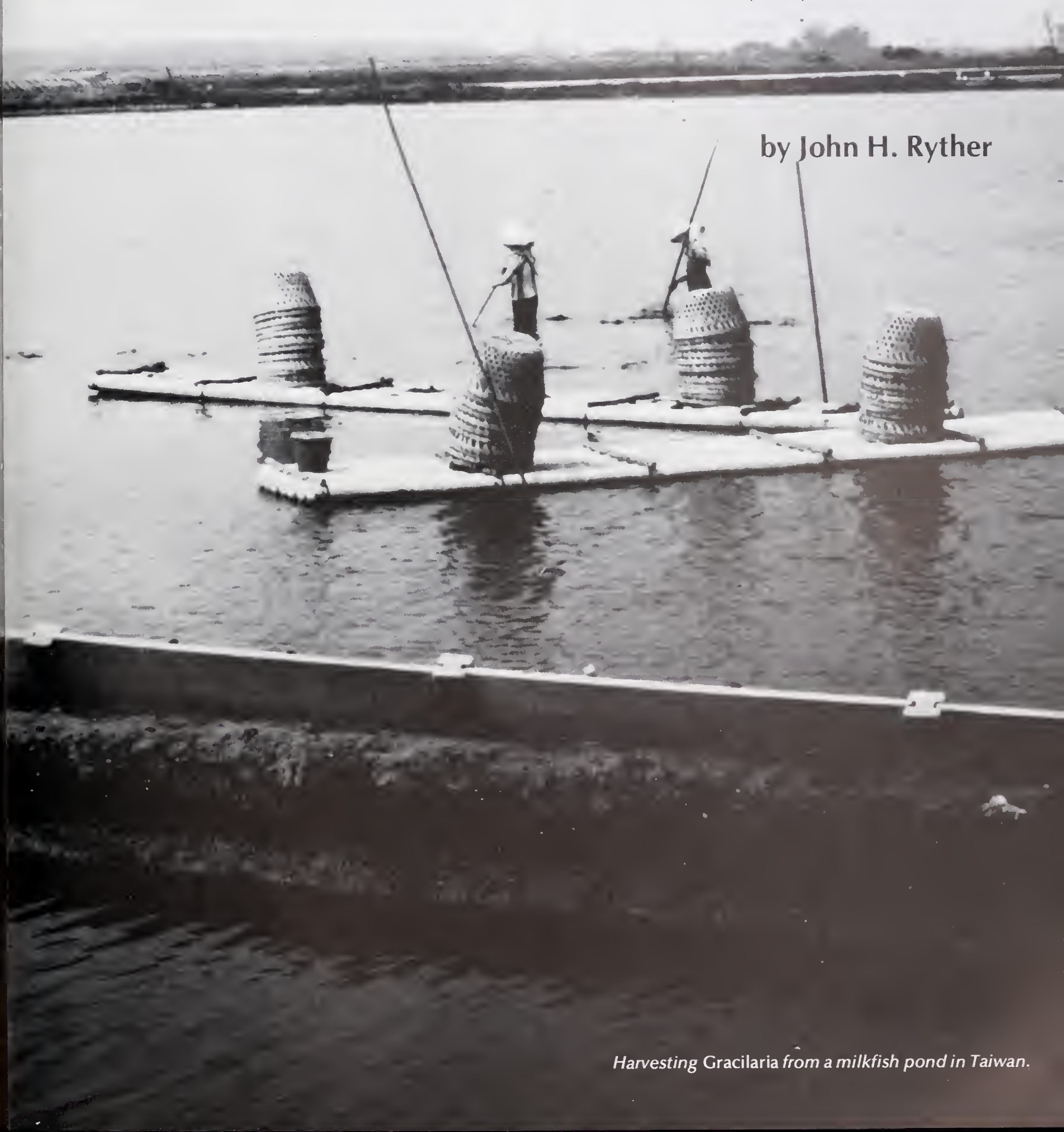


Two engineers at Lockheed Corporation have developed an interesting ocean wave energy device called Dam-Atoll that is depicted in the rendering and cutaway above. Waves enter an opening at the top of the unit, just at the ocean's surface. A set of guide vanes at the opening causes the entering water to spiral into a whirlpool, held inside a 60-foot-deep central core. The swirling column of water in the central core turns a turbine wheel, the unit's only moving part, which provides a continuous electrical power output of 1 to 2 megawatts, according to the inventors, Leslie S. Wirt and Duane L. Morrow. The inventors, who spent six years of research on the concept culminating in a patent in January of 1979, envision anchoring the Dam-Atolls off the windy beaches of the world, where there is about 40 megawatts of power available per kilometer of beach, or enough to provide about 40,000 individuals with their domestic power requirements. In particularly good wave areas, such as the Pacific Northwest, they believe it would be possible to anchor 500 to 1,000 of these units, providing power comparable to that of Hoover Dam. The device, 250 feet in diameter and made of concrete, has many potential uses other than the generation of electricity, such as cleaning up and recovering oil spills, protecting beaches from wave erosion, forming calm harbors in the open sea, and desalinating seawater through the process of reverse osmosis.

Fuels

from Marine Biomass

by John H. Ryther



Harvesting Gracilaria *from a milkfish pond in Taiwan.*

Of the various existing and proposed methods of utilizing solar energy, the production of fuels from new, photosynthetically produced organic matter — biomass in the present terminology — is both one of the simplest and most complicated. The technology is simple. Dried plant biomass may be burned directly. That, indeed, is man's original source of energy, and firewood is still a familiar fuel in much of the United States — one that appears destined to revive in importance.

But plant biomass must be relatively dry for direct combustion to occur. Unlike seasoned wood, most freshly harvested plant material contains 85 to 95 percent water, which cannot be easily or economically removed — more energy may be expended in removing it than can be gained in the final product. Another drawback is that several essential plant nutrients, particularly nitrogen, are vaporized and lost when direct combustion occurs. The energy cost of converting atmospheric nitrogen to fertilizer is some 74,000 BTUs* per kilogram, nearly half the total energy requirement for producing agricultural crops in the United States. The loss of nitrogen and other volatile nutrients by combustion is thus a serious energy loss and inefficiency in the system.

An alternative method for obtaining power, or at least fuel, from wet plant biomass is that of anaerobic digestion.** Sugar plants (cane, beets, sorghum) have a distinct advantage in this respect, because much of their biomass is directly fermentable to liquid fuel (ethanol). However, the area in which such plants may be grown is severely limited in the United States. This is because they also are seasonal crops and their yields are accordingly restricted. Some sugar crops in the United States are already contributing to the production of "gasohol" as an automotive fuel, but the supply of energy from that source is likely to be limited.

However, virtually all wet plant biomass readily undergoes a more complete anaerobic decomposition or fermentation, with the ultimate production of gas being a mixture of carbon dioxide and methane. These gases have heating values of 500 to 800 BTUs per standard cubic foot and can be readily upgraded to gas of pipeline quality by established processes. Water slurries are required for digestion to take place and many freshly harvested plant species hold much of the needed water in their tissues. Further, it has been demonstrated that the liquid and solid residues from anaerobic digestion contain all of the nutrients, including nitrogen, originally present in the plant biomass. These residues are effective fertilizers and used as such allow recycling of the nutrients into new plant crops.

The difficulty with all of these approaches lies in the fact that vast quantities of biomass are needed to make a significant contribution to the energy budget of the United States. The energy content of most organic matter, including seasoned firewood, is on the order of 20 million BTUs per dry metric ton. The best yields from silviculture are roughly 5 and 10 dry metric tons per acre per year from deciduous and evergreen forests, respectively. To provide the energy equivalent in firewood of a single 1,000 megawatt fossil fuel or nuclear power plant would thus require a managed energy farm on the order of 100,000 acres, or about 100 square miles, a sizable piece of real estate.

With respect to the anaerobic digestion of wet plant biomass, about half of most organic matter is capable of being fermented to a low-grade (50 to 60 percent methane) gas mixture. Furthermore, the nonorganic, mineral content of vegetation ranges from 10 to 20 percent of the total dry weight of terrestrial and freshwater plants to as much as 50 percent of most marine species, so the amount of energy as methane that may be produced per ton of dry plant biomass from fermentation is no more than 2.5 to 5 million BTUs, depending on the crop.

Agricultural crops, grasslands, and other forms of terrestrial vegetation in the continental United States are, on the average, less productive than the forest trees previously cited. The mean annual yield of corn, the most productive temperate crop in the United States, is no more than 5 dry tons per acre, including residues (about 45 percent of the total plant biomass). About a billion acres in this country are presently used for the production of 1.2 billion tons of grains and grasses — an overall average of just about a ton per acre per year. The energy potential of these relatively low yields, converted to methane by the rather inefficient process of anaerobic digestion, means that some ten million acres of cropland would be needed to produce the energy equivalent of one 1,000-megawatt power plant — that being the gross output uncorrected for the energy input for growing, harvesting, transporting, processing, and fermenting the biomass, and for upgrading, transmitting, or storing the gas product.

These areal requirements appear to be unreasonably high for either economic or energy-based cost effectiveness, but the best agricultural land in the country — that capable of producing even the modest agricultural yields previously discussed — is already fully used for the production of food and fiber crops. These crops, for the most part, are worth 10 to 100 times the value of the corresponding biomass for fuel. Even at a

*British Thermal Units. A BTU is the amount of heat necessary to raise one pint of water one degree Fahrenheit.

**Liberation of energy by breakdown of substances not involving consumption of oxygen.

deregulated price of $5.00 per thousand cubic feet, the amount of methane that could be produced by anaerobic digestion from a ton of a typical agricultural crop (fresh or wet weight) would be worth no more than about $2.50, roughly a tenth of a cent per pound.

There are, of course, agricultural residues — as much as half the total organic production — that are usually treated as wastes. Where these are left in the fields, they are usually plowed under and are considered an essential ingredient in replenishing the nutrients and quality of the soil. Where these residues are generated at the food (or lumber, or other) processing site, their direct utilization or conversion to fuel makes a great deal of sense, and such practices are now being implemented.

In short, with the exceptions of wood and certain agricultural wastes that may be burned directly, and a few special crops that may be converted directly to liquid fuel, the conventional agricultural crops, grasses, and other forms of terrestrial vegetation do not appear to hold much promise as a major source of energy for the United States.

Does the general "fuels from biomass" concept, then, have any validity and, if so, what kinds of biomass could conceivably be grown for that purpose? It appears that species not presently cultivated must be grown for this new purpose, and that they also must be grown in areas unsuitable for the cultivation of food and fiber crops. They also must be highly productive and easy and inexpensive to grow, harvest, and process.

Enter Seaweeds

Seaweeds appear to meet most of these requirements. Certainly, the oceans are the largest uncultivated and under-utilized pastures on earth. In eastern countries, some species of seaweed do have commercial value as food, and for their contained chemicals — hydrocolloids, such as agar, alginic acid, and carrageenan. These hydrocolloids are used as emulsifiers and stabilizers in the food and drug industries, but the market is limited. Other species are used on a limited basis for such low-value purposes as cattle feed, compost, and fertilizers. Most seaweeds have no commercial value and some (for example, *Ulva* or sea lettuce) are considered aesthetic nuisances when they grow or accumulate to high densities in heavily populated bays and estuaries. In general, cultivation of seaweeds for energy would not compete for production of food or fiber crops in terms of space, effort, or economics.

A few of the seaweeds used as food have been cultivated for a number of years in the Far East and, more recently, some have been grown for their hydrocolloids, though that industry still relies primarily on the harvest of natural populations. Cultivation of the food species, for the most part,

Sugar cane field in United States. Crop is used for production of "gasohol." (Photo courtesy Department of Energy)

has employed intensive labor practices and a rather primitive technology. Yields from such practices range from less than a dry ton per acre per year for the highly prized *Porphyra* or "nori" in Japan (whose price of more than $20 per pound justifies this high-labor, low-yield activity) to a somewhat more impressive 20 tons per acre per year for kelp grown in northern China (Table 1). The latter rivals the more productive terrestrial crops, such as napier grass and sugar cane, experimental yields of which have been reported recently in Puerto Rico at 26 and 22 dry tons per acre per year, respectively. Seaweeds grown for their hydrocolloids — *Gelidium* in Japan, *Gracilaria* in Taiwan, *Eucheuma* in the Philippines — produce yields that are intermediate between nori and kelp, averaging about 5 dry tons per acre per year.

The red seaweed *Chondrus crispus*, commonly known as Irish moss, has been long harvested from natural beds in New England, the Canadian maritimes, and northern Europe for extraction of its hydrocolloid, carrageenan. Because of dwindling natural resources, attention began to focus on the artificial cultivation of the species, beginning in the late 1960s. The pioneer work in this area was carried out by A. C. Neish and his collaborators at the Canadian National Research Council, Atlantic Regional Laboratory, Halifax, Nova Scotia.

In the course of his studies, Neish developed an interesting new technique for growing *Chondrus*. Although in its natural habitat the seaweed grows attached to rocks or other substrata on the bottom, Neish found that it would grow more rapidly if it were maintained suspended in the water by either water currents or vigorous aeration. Furthermore, the suspended cultures maintained themselves permanently in a vegetative, nonreproductive, nonfruiting stage. The latter represents a distinct advantage for biomass production over the normal plants that periodically

Table 1. Summary of yields from commercial seaweed culture.

Species	Location	Yield dry tons/ acre/year
Porphyra (nori)	Japan	0.1-1.3
Porphyra (nori)	China	0.2-3.4
Undaria (wakami)	Japan	1.9
Gelidium	Japan	2.1-5.0
Laminaria (kelp)	China	12-20
Gracilaria	Taiwan	4-8
Eucheuma	Philippines	5

become reproductive, cease vegetative growth, and usually disintegrate after release of the reproductive spores or gametes.

This author adopted Neish's technique for growing seaweeds at the Woods Hole Oceanographic Institution as part of a waste recycling/aquaculture project. In this project, the plants were used as a polishing stage to remove the nutrients generated by a shellfish culture system prior to discharge of the aquaculture effluent to the environment. Although Irish moss also was initially used in these studies, other commercially valuable species of red algae were subsequently found to grow better in the Woods Hole area, particularly in summer, when the water temperature exceeded the optimum for the cold-adapted *Chondrus*. It also was found that the same seaweeds grew particularly well in seawater enriched with domestic sewage effluent. In this instance, they were equally effective in removing the nutrients, particularly nitrogen, from the wastewater. Thus seaweed culture, in addition to producing a valuable crop — worth $500 to $1,000 per dry ton on the present, somewhat limited market — can serve as a biological tertiary sewage treatment system by removing the nutrients from the effluent of secondary sewage treatment.

When the Energy Research and Development Administration (ERDA), precursor of the Department of Energy (DOE), developed its "Fuels from Biomass" program in the mid-1970s, the search began for highly productive plant species that could be grown over vast areas as "energy farms." These farms would be capable of providing the organic biomass needed to make a significant contribution to the country's energy needs — then pegged at some 75 quads (quadrillion or 10^{15} BTU) per year, with more than 100 quads predicted by the turn of the century. Because of the promising preliminary results with seaweed culture in the Woods Hole aquaculture project, support was obtained to investigate the potential of seaweeds as a "biomass for energy" source. At that point, the research was transferred to the Harbor Branch Foundation laboratories in Fort Pierce, Florida, because the milder climate of that location would permit year-round growth of the plants, thereby better reflecting the maximum potential of seaweeds for organic production.

Gracilaria *grown on rope.*

No longer restricted to species of commercial value, the Florida research focused on the selection of the best species for biomass production. This meant that we were looking for the species with the highest rate of organic productivity per unit of area throughout the year; that maintained itself indefinitely in a nonreproducing, vegetative growth phase; and that was easiest and least costly to grow, with minimal problems and complications during its cultivation.

More than 50 species of seaweeds native to Florida coastal waters, including representatives of all of the major taxonomic groups — green, red, and brown algae — were screened in small (50-liter) outdoor culture units. Surprisingly, the best candidate was a red seaweed containing agar, *Gracilaria tikvahiae*, that had previously been grown in the Woods Hole experiments.

Gracilaria was then grown throughout an entire year in the small screening units. Under what appeared to be ideal culture conditions — vigorous aeration, rapid exchange of seawater (30 culture volumes per day or a retention time of 0.03 days) enriched with nitrogen, phosphorus, and trace nutrients, and with frequent (one- to two-week) harvests to maintain the plants at their optimal density for best growth — the annual production of the seaweed averaged 35 grams dry weight per square meter per day (equivalent to 51 dry tons per acre per year).

It is, of course, misleading to extrapolate small-scale experimental results to large areas where scaling factors and other complications may lead to significantly lower yields. However, the production potentials of many terrestrial crops have been evaluated in similar, small-scale experimental plots. None has surpassed that of *Gracilaria.* It must be remembered, however, that *Gracilaria,* like other seaweeds, contains a large fraction of its dry weight as mineral salts. Ironically, the more ideal the culture conditions, particularly with respect to the supply of essential nutrients, the greater the mineral or "ash" content of the plants. Those grown in the experiment previously described have an ash content of approximately 50 percent of their total dry weight. But the purely organic yield of 25.5 tons per acre per year still exceeds that of almost any other plant on earth for which there is well-documented evidence, the only possible exceptions being sugar cane grown in the tropics, the freshwater macrophyte water hyacinth, and perhaps a few tropical grasses.

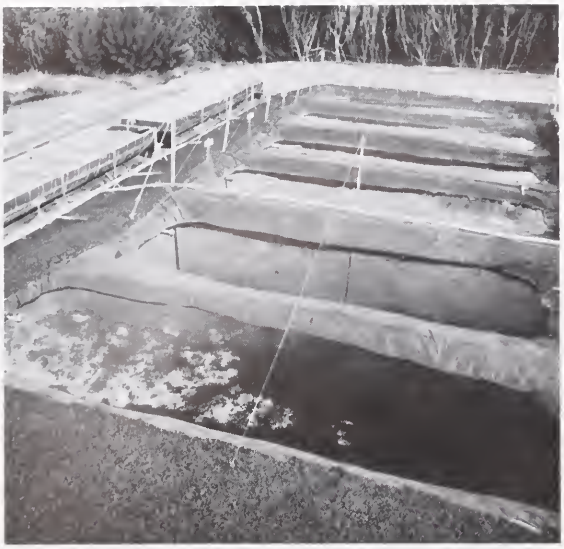
Unfortunately, any departure from the highly idealized culture conditions described previously results in sharply curtailed yields of *Gracilaria.* In a subsequent experiment in which the seaweed was grown in a much larger (2,600-liter) volume with only four exchanges of water per day (0.25 per day retention), the annual yield was reduced by 40 percent.

As mentioned earlier, *Gracilaria* is grown commercially in southern Taiwan in shallow 2- to 3-acre ponds (average size) that were originally constructed for the cultivation of milkfish. The practice involves one or more species that appear to be different from those used in Florida, though the systematics of this large and ubiquitous genus are far from clear. The seaweed is grown on the bottom of the ponds, which range from ¼ to 1 meter in depth, depending on the season. The water in the ponds is exchanged sporadically with the adjacent estuary, at intervals of days to weeks as needed to control temperature and salinity, but it usually is not enriched. The seaweed is harvested seven or eight times a year by dip-netting a portion of the population and spreading the remainder evenly over the bottom.

This relatively passive, nonintensive culture technique results in a yield of about 5 dry tons per acre per year, only 10 percent of that achieved in Florida using the more intensive culture method and where the climate is comparable to southern Taiwan. Thus, as a rule of thumb, it would appear that the more intensive the culture system, the higher the yield. None of these culture systems has been subjected to either economic analysis or evaluation of energy input/output ratio, but it would seem most unlikely that an expanded version of the small, intensive experimental unit, involving vigorous aeration and rapid exchange of water, could prove viable from either point of view. Attempts are now being made to develop a culture system that is a compromise between the low-cost Taiwanese technology and the intensive Florida system — one that could result in yields intermediate between the two that would be competitive relative to plant biomass production elsewhere.

The 50-liter test system for screening seaweeds in Florida.

Equally important, however, is the development of a culture method whereby the plants can be grown offshore in the open ocean.



PVC-lined earthen ponds (right) and aluminium tanks (left) used for growing seaweeds at the Harbor Branch Foundation, Fort Pierce, Florida.

Since seaweeds normally grow attached to the bottom, they are restricted in their natural distribution to the shallow fringes of the sea — water depths usually of less than 10 and never exceeding 100 meters. The few culture operations are similarly restricted to shallow coastal waters or to impoundments on land, as in the Taiwanese *Gracilaria* industry. But coastal lands and waters are among the most costly and heavily used parts of our country. If prime agricultural land is in heavy demand for food production, the coastal zone is in even heavier demand for that and almost every other form of human activity, including industry, housing, recreation, transportation, and waste disposal, among others, many of which are already in conflict with each other. Large-scale energy farming could not possibly compete with these multiple uses. Rather, it would have to be conducted offshore in the relatively inaccessible and little-used parts of the oceans. This imposes new problems, both technical and economic. New methods must be developed for growing seaweeds offshore, at or near the sea surface, within relatively shallow depths where there is sufficient light for photosynthesis to occur. These seaweeds would be grown in trays or baskets, on nets, or woven into ropes, or in or on some type of structure that is moored or suspended in such a way as to withstand environmental pressures, such as waves, currents, and storms.

Preliminary experiments have been initiated in Florida to develop such techniques for offshore culture of *Gracilaria,* but perhaps, in the long run, some other species of seaweed will turn out to be better adapted to cultivation in the open sea. The ubiquitous brown alga *Sargassum* is a logical candidate, since it occurs naturally in the central gyres of the oceans, where it lives at the surface, buoyed by small floats or bladders. Such a floating habit is an obvious advantage in open-ocean culture, eliminating the need for costly suspension structures. One species, *Sargassum natans,* which gives the Sargasso Sea its name, grows only vegetatively, never having been known to produce or bear fruiting, reproductive bodies. Unfortunately, the evidence to date indicates that the drifting species of *Sargassum* grow very slowly, but more work needs to be done with that otherwise promising genus.

Giant Kelp a Possible Energy Source

Another very attractive candidate for offshore marine biomass production is the giant kelp *Macrocystis pyrifera.** This large alga, which may reach 50 meters or more in length, is one of the most important resources along the California coastline, not only because it has a high commercial value, but also because it is the dominant species and habitat of the local ecosystem.

Commercial interest in the kelp beds of California began in 1910, when the Bureau of Soils of the Department of Agriculture conducted a survey of possible sources of potash within the United States. The location of three kelp genera that are high in potassium — *Alaria, Macrocystis,* and *Nereocystis* — was mapped, with plant densities qualitatively assessed. Realizing the commercial potential of kelp, companies soon formed to harvest and process the brown algae. With the advent of World War I, German potash sources were completely eliminated, and the annual harvest of kelp in California increased to 130,000 in 1916 from about 2,500 tons in 1913. By the end of the war in 1918, the demand for kelp had totally collapsed in the United States, and it remained negligible until the early 1930s. Since that time, the annual recoveries of kelp from California beds have steadily increased to a point where they now support highly profitable enterprises. At present, a polysaccharide, algin, is the major chemical product extracted from California kelp by two processors, Kelco and Stauffer chemical companies.

Early methods for harvesting giant kelp plants were rather crude and often destructive. A large

*This section on giant kelp is taken from a special topical report by E. H. Wilson, J. C. Goldman, and J. H. Ryther on sources and systems for aquatic biomass as an energy resource, which is part of the cost analysis of algal biomass systems by Dynatech R/D Company referred to on page 57. It is based on material provided by Professor Wheeler J. North of the California Institute of Technology.

number of plants were "lassoed" with a cable and drawn into a tight bundle for cutting. The cut kelp fronds were then either pulled aboard a vessel by hand or allowed to drift ashore for collection. As the need for larger quantities of kelp developed, more efficient harvesting methods were employed, giving rise to a moving barge with a trapper bin for bringing cut material on board and storing it. Present-day harvest vessels are equipped with reciprocating underwater mowers at the stern and a conveyor belt for moving the cut kelp aboard.

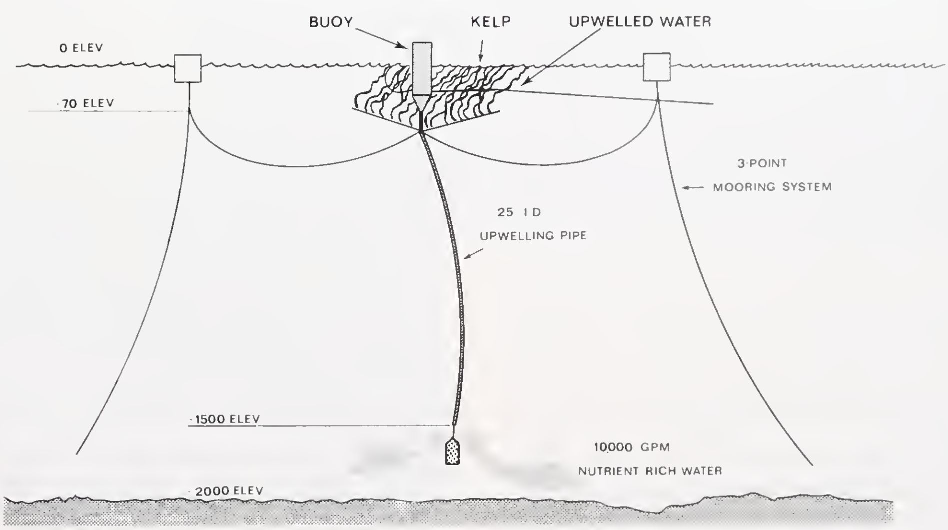
The kelp beds presently are leased by the State of California and controlled by licensing and royalty arrangements. Regulation of the kelp beds began in 1916 when representatives from the kelp farms, the U.S. Department of Agriculture, the University of California, and the California Fish and Game Commission set forth a foundation for controlled utilization and conservation of kelp bed resources. The resulting regulations have proved successful in accurately monitoring and controlling kelp harvests and consequently conserving kelp beds.

In the mid-1950s, concerned biologists, government officials, and industrial leaders began to notice a decline in the standing crop of the nearly 250 square kilometers of kelp forest along the California coast. Wheeler North, then of the University of California's Institute of Marine Resources, initiated a study to determine whether the decline was caused by overharvesting or was the result of a biological occurrence, such as grazing by sea urchins, or physical parameters, such as water pollution or a temperature change. These studies were the beginning of a series of research projects that have continued for more than 20 years. Numerous research projects by North and others on the life history, growth and reproduction, and transplantation of *Macrocystis* led to the development of techniques for reestablishing kelp beds.

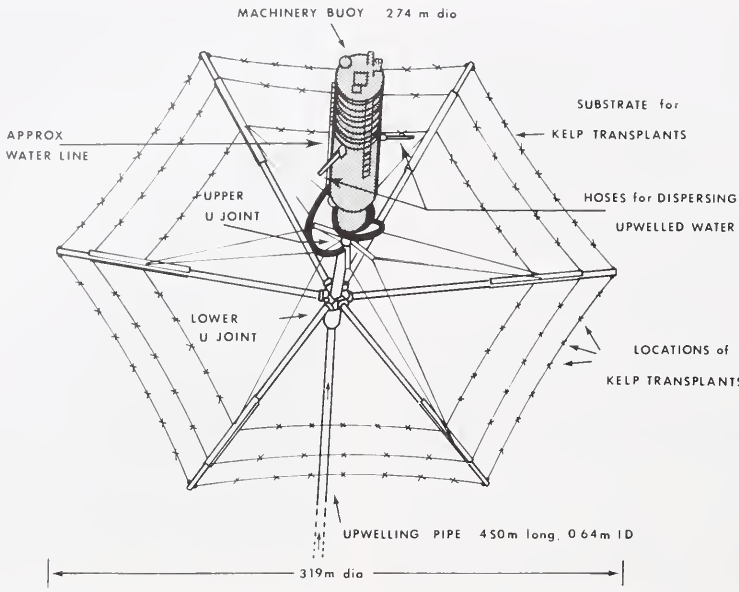
Because of the overwhelming success of restoration efforts, the potential for cultivating *Macrocystis* in new areas was recognized. In the mid-1970s, an ambitious Ocean Food and Energy Farm (OFEF) program was begun — funded jointly by the Energy Research and Development Association, the National Science Foundation, the American Gas Association (AGA), the U.S. Navy, and various organizations in public and private sectors. The primary objective of the farm was to cultivate kelp as a source of energy. An ocean farm system was designed under the management of H. A. Wilcox of the Naval Undersea Center, San Diego.

The design consisted of an open-ocean farm covering 100,000 acres, 12.5 miles on a side, located 100 miles off the coast of southern California. After survey studies, three sites in southern California were recommended. The farm substrate, maintained at a depth of approximately 100 feet, was to be made up of flexible triangular modules 1,000 feet on a side, each covering about 10 acres. Each module would be held in place by diesel-powered propulsors. Nutrient-rich water was to be upwelled from a depth of about 300 feet by wave-powered pumps. The upwelling pumps considered for the project included the Isaacs buoy propeller pump, a wave turbine propeller pump, a windmill propeller pump, a wave vane propeller pump, a modified Isaacs pump, and the Wilcox bellows pump.

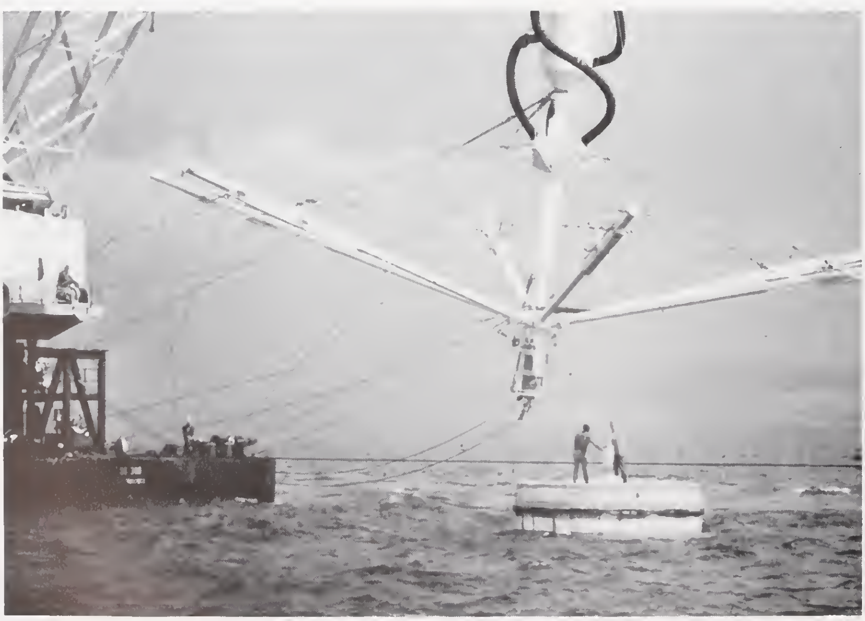
Kelp plants, attached to the substrate at a density of one plant per 363 square feet, would take about four years to mature; then the standing crop would be harvested by ship six times per year. The



General arrangement of Test Farm off Laguna Beach, California.



Underwater umbrella-like arrangement for kelp transplants.



Buoy and device for kelp transplants being readied at sea.

estimated yield of the farm was about 15 dry tons per acre per year of which eight tons would be organic biomass. By comparison, the average harvest yield of natural kelp beds is estimated by North and others as ½ dry ton per acre per year.

A barge-type concrete platform would be provided for living, and work space for operating and maintaining the farm. The kelp would be processed to produce methane and by-products. Along with the kelp cultivation, the system included the mariculture of noncompetitive organisms, such as kelp bass and oysters.

To test the technical and economic feasibility of the commercial-sized ocean energy farm, a research program was begun in 1976 jointly sponsored by ERDA (subsequently DOE) and AGA, and managed by the General Electric Company. Scientific and engineering support is provided by the Institute of Gas Technology, the U.S. Department of Agriculture, and Global Marine Development, Inc. Under this program, a modular structure called the Test Farm, reminiscent of a

Kelp transplants on Test Farm.

Upwelling pipe being towed to sea.

single unit from Wilcox's sea farm, was installed at a site off Laguna Beach, California. The Test Farm consisted of a 9-foot diameter buoy that stands upright in the water and is attached by a universal joint to an umbrella-shaped set of radial arms to which kelp plants may be attached. Nutrient-rich water is pumped from depths of about 1,500 feet, up through a 2-foot diameter polyethylene pipe, using three pumps with capacities of 3,500 gallons per minute, driven by 20 horsepower diesels. The Test Farm was deployed at sea in September 1978, and thereafter was supplied with 103 adult kelp transplants, but because of several technical problems, the initial plantings failed to survive. The adult plants, however, did "seed" the solid structures of the Farm with spores which, in turn, yielded an estimated 30,000 juvenile plants. The crop of juveniles is presently under intensive study. A second test of the system was in preparation at the time this article was being written. In the meantime, a DOE-sponsored engineering and economic analysis of a number of proposed aquatic biomass energy farms, including both freshwater and marine species and unicellular algae as well as seaweeds and higher plants, carried out by the Dynatech Research and Development Company of Cambridge, Massachusetts, cast some doubt on the cost-effectiveness of the proposed kelp farm, with respect to economics and the energy input/output ratio.

Much depends in such analyses on the projected organic yield of the system, which now covers a range of uncertainty of nearly two full orders of magnitude — from estimates of less than 10 by skeptics to more than 100 ash-free dry tons per acre per year by proponents of the scheme. Such

speculation results from the lack of hard data on kelp production under ideal conditions, including continuous nutrient enrichment. In all likelihood, the potential is not greatly different from that of *Gracilaria* and other seaweeds, whereas that attainable by any economically viable, nonenergy-intensive large-scale farming practice, as in agriculture, will fall well below that potential.

One of the major economic and energy costs of the ocean kelp farm, according to the Dynatech analysis, is that of pumping the nutrient-rich deep water to the surface, wind and wave power having been considered inadequate for the purpose. An alternative method of providing nutrients to the seaweeds, mentioned earlier, would be to recycle the liquid residues after methane generation of the wet biomass. Preliminary experiments with anaerobic digestion of *Gracilaria* in Florida have shown that nearly three-quarters of the nitrogen content of the seaweed is left in the liquid residue and is available as a nutrient for further growth of the plant.

Such nutrient recycling undoubtedly would mean that the methane generation phase of the operation would have to be closely coupled physically with the biomass production, and thus, in the case of an open-ocean energy farm, would have to be done at sea. This could result in further savings of the cost of transporting the bulky and heavy wet biomass of seaweed to a land site for digestion. It would mean, however, that the gas would have to be shipped ashore, presumably by pipeline or vessel. Since complete nutrient recycling is not feasible, an additional supply of nutrients would still be necessary. Perhaps the pumping of deep water by wind or wave power for such supplemental enrichment would prove possible.

Much Remains to be Learned

Seaweed culture as a large-scale commercial operation is still very much in its infancy. The few practices scattered around the world for the most part are primitive and make little use of modern technology. Much remains to be learned about the basic biology of the plants, particularly their nutrition and growth, and factors that control their organic productivity. The much more difficult task of developing a technology for growing seaweeds in the open sea must await our ability to grow them in small, controlled experimental units on land, or in protected coastal areas, and to fully understand and define their growth potential under different conditions. In short, open-ocean energy farming of seaweeds must be regarded as a long-term prospect that cannot be expected to be realized in a time frame of less than tens of years.

It is hoped that decisions based on the limited success of pioneer efforts do not prematurely eliminate open-ocean energy farms from further consideration. For the ocean is just about the only place on earth where truly large-scale biomass production, capable of contributing significantly to the world's energy budget on a noncompetitive basis with man's other space needs, could conceivably be carried out.

John H. Ryther is a Senior Scientist in the Biology Department at the Woods Hole Oceanographic Institution.

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Chemosynthetic Production of Biomass:

an idea from a recent oceanographic discovery

by Holger W. Jannasch

The generation of biomass from carbon dioxide (CO_2) is called "primary production" because it is the first, fundamental step in turning inorganic material into organic compounds and cell constituents. This "photosynthetic" reduction of CO_2 is carried out by plants that use light as the source of energy. All life depends on this primary production and is thus maintained by solar energy. In turn, the formation of animal biomass from plant materials is termed "secondary production." It is, however, rather a conversion, whereby some of the organic matter is oxidized back to CO_2 to provide the necessary energy. Chemosynthesis is another type of primary production of organic matter.

Photosynthesis and Chemosynthesis

It is not only the energy that is important. Using the analogy of the water wheel, it is not only the elevation of water that is needed to turn the wheel, but also the water itself. The flow of water compares to the flow of electrons. Hydrogen sulfide was used as a source of electrons by the earliest primary producers, the photosynthetic purple bacteria, in the anoxic primordial biosphere of the globe. During the course of evolution, light-absorbing pigments and the mode of electron transfer developed further, and, at a critical point, blue-green bacteria converted to using H_2O (water) instead of H_2S (hydrogen sulfide) as the source of electrons. As a waste product of the oxidation of water, free oxygen emerged in the atmosphere. Since free oxygen reacts spontaneously with many potential electron sources, thereby competing with life processes, it acts like a poison for anaerobic organisms and might have been the first instance of a deadly pollutant. As a result of the subsequent evolution of green plants, our present atmosphere contains about 21 percent free oxygen. A complex system of enzymes allows the aerobic organisms, including humans, to cope through an intricate electron transfer system with the high reactivity of free oxygen.

Where does chemosynthesis fit into the picture? Instead of using light for the reduction of carbon dioxide, some bacteria used the energy liberated by the oxidation of certain electron

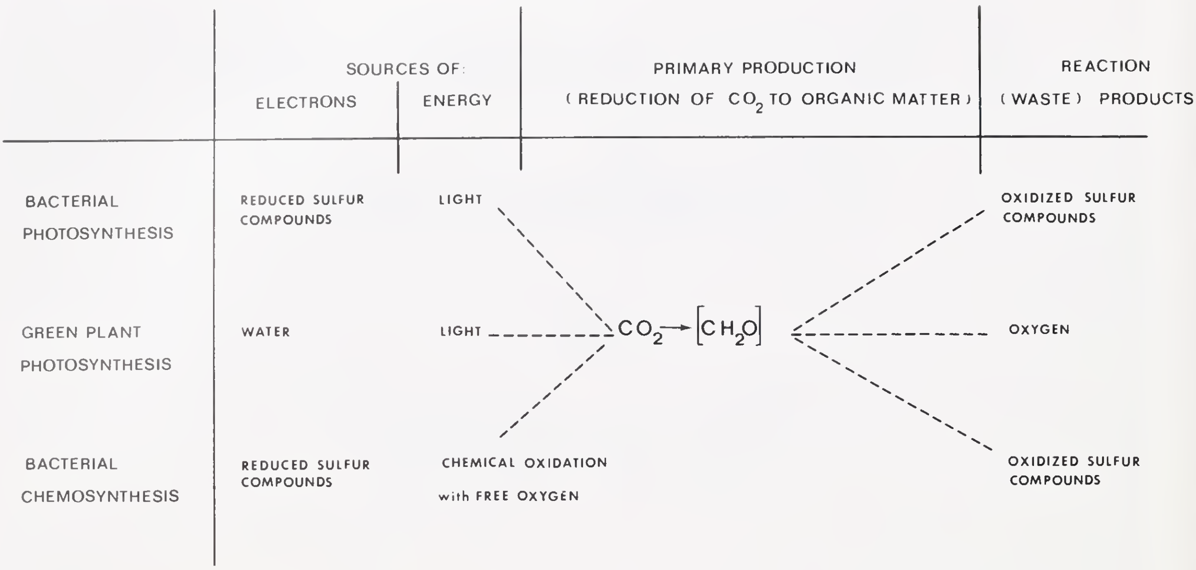

Figure 1. The three types of primary production. Bacterial chemosynthesis also can be based on the chemical oxidation of a number of other reduced inorganic compounds.

sources with free oxygen. Thus, in the course of evolution, these aerobic organisms emerged after the appearance of free oxygen. Since they use chemical energy instead of light, they produce organic matter chemosynthetically and not photosynthetically (Figure 1). For energy, they use hydrogen sulfide and other sulfur compounds, such as elemental sulfur (S°) and thiosulfate ($S_2O_3^{2-}$), in addition to hydrogen (H_2), ammonia (NH_3), nitrite (NO_2^-), reduced iron (Fe^{2+}), and probably other metals, such as manganese. Chemosynthesis is limited to special locations and situations where those reduced compounds meet with free oxygen.

These chemosynthetic or "chemolithotrophic" (lith-= stone, mineral; troph-= nourish) organisms have been known to microbiologists for some time. Their contribution to the primary production of organic matter in ecosystems, however, has never proved to be substantial. Since hydrogen sulfide is found predominantly in the oxic/anoxic interfaces of marine basins — such as observed in the Black Sea, the Cariaco Trench, or shallow estuarine waters — chemosynthetic production has been studied mainly in these environments. But even in such areas, it always has been found to be negligible in comparison with photosynthetic production.

The source of hydrogen sulfide in those marine environments is primarily a result of biogenic sulfate reduction, another microbial process. This process is driven by energy derived from the oxidation of organic matter originally produced by photosynthesis, that is, solar energy. In contrast, the sulfide content of volcanic fumaroles and hot springs found on the continents is of geothermic origin. At high temperatures and pressures, sulfur and other elements are leached from rocks and emerge at the surface dissolved in the spring water. Thus geothermic energy is converted into geochemical energy by "reducing" these elements — that is, combining them with hydrogen or electrons as in $S^{\circ} \rightarrow H_2S$ (sulfur→hydrogen sulfide). When these potential electron sources meet with free oxygen, the energy is recovered in the oxidation process. The chemosynthetic bacteria use sulfide, the origin of which can be traced back to the expenditure of either solar or geothermic energy.

The Galápagos Rift Thermal Springs

The notion that chemosynthetic production amounts to only a negligible or small fraction of an ecosystem was shattered when the first deep-sea thermal springs were discovered. The geological, geochemical, and biological aspects of this discovery were published in *Oceanus*, Vol. 20, No. 3 and Vol. 22, No. 2, and by Corliss and others, 1979. In essence, these submarine thermal vents found at a depth of 2,550 meters were surrounded by thick clusters of unusually large specimens of mussels (Figure 2), clams, vestimentiferan tube worms, and many other known and unknown invertebrates. It was hard to imagine that these dense populations, tightly concentrated around the vents almost two miles below the surface, could be directly or indirectly supported by photosynthetically produced organic matter.

Since the water emitted from the vents had a milky appearance and was found to contain hydrogen sulfide, it was readily suspected that

chemosynthesis was the primary source of organic nutrients. Thus, it was hypothesized that the food chain began with the production of bacterial biomass, which led to the massive but highly localized animal communities. The preliminary microbiological work done during the January 1979 expedition to the Galápagos Rift area confirmed that there is, indeed, a high production of bacterial biomass in the water emitted from the vents (Jannasch and Wirsen, 1979). Up to a million bacterial cells (Figure 3) per cubic centimeter of water were found. The actual number is probably much higher since the sample was collected 1 meter above a vent where the emitted water is already diluted by ambient seawater.

In addition, the concentration of ATP (adenosine triphosphate), used as an indirect measure of living microbial biomass, was found to be two to four times higher than in the surface waters inhabited by phytoplankton of the same region, and two to three orders of magnitude higher than in deep water sampled some distance away from the vents (Karl and others, 1979). Some 200 strains of bacteria were isolated and are now under study, all of them capable of oxidizing sulfur compounds. Some of the other chemosynthetically oxidizable compounds mentioned previously are also found in the vent waters. The mere abundance of sulfur compounds leads us to conclude that the major portion of chemosynthesis is carried out by sulfur-oxidizing bacteria.

The mussels and clams (and, in one vent, the

Figure 2. The turbidity in the water emitted from the Galápagos Rift vents is primarily caused by oxidation of hydrogen sulfide to colloidal and particulate sulfur and by the chemosynthetic production of bacterial cells. Large mussels of up to 20 centimeters in length cluster around the vents. (Photo by J. F. Grassle)

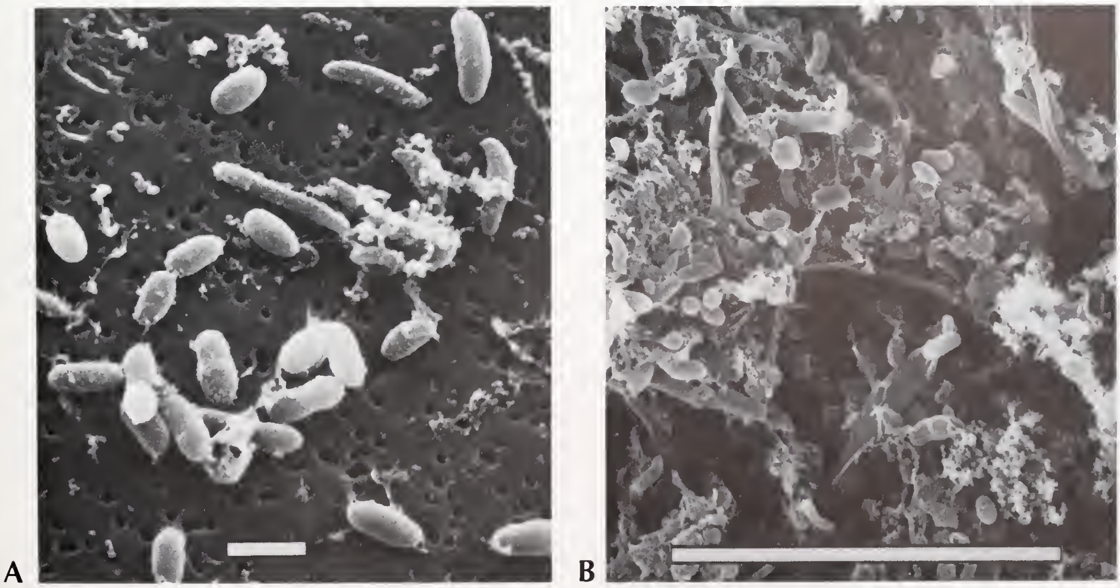

Figure 3. Scanning electron micrographs of the suspended matter in the turbid water collected from one of the Galápagos Rift vents on a Nucleopore filter. A: freely suspended bacterial cells (bar=1 micron); B: surface section of a large clump, containing bacterial cells and amorphous material, primarily sulfur (bar=10 microns). (From Jannasch and Wirsen, 1979; photo by E. Seling)

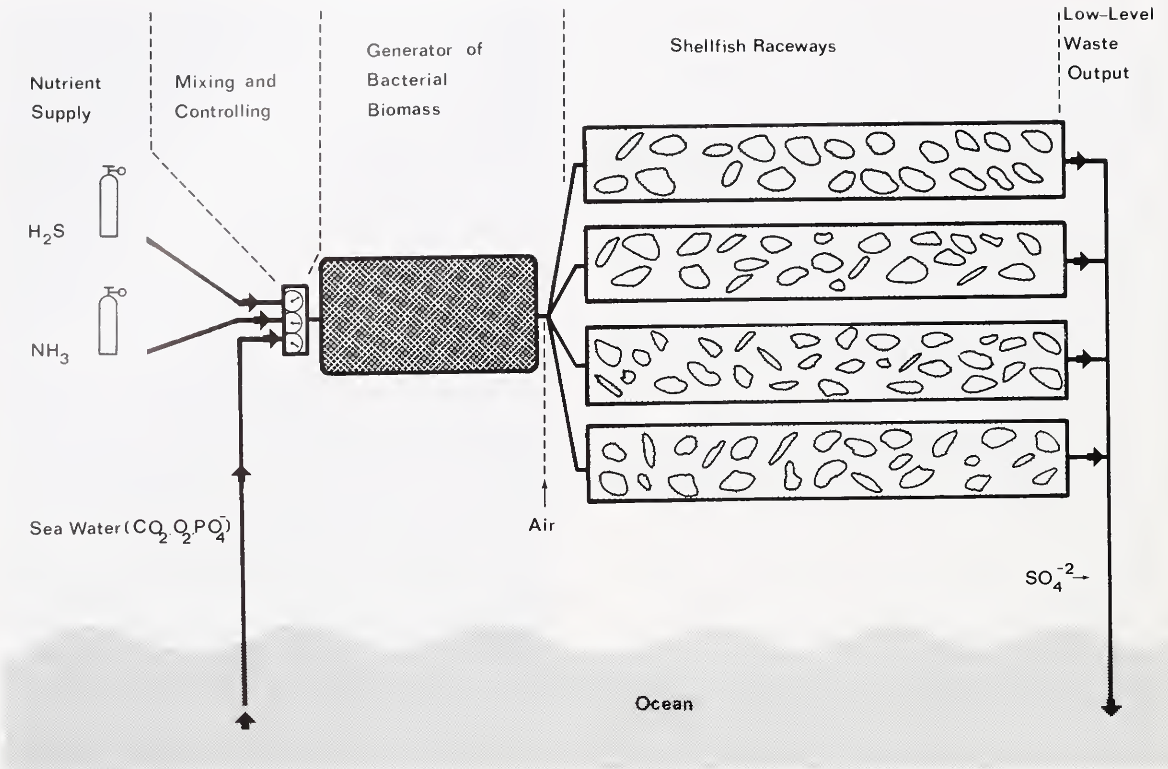

Figure 4. Plan of aquaculture system based on the oxidation of hydrogen sulfide by chemosynthetic bacteria.

vestimentiferan tube worms) are by far the most conspicuous and massive of the animal populations surrounding the vents. They appear to constitute the largest portion of biomass originated by secondary production. All our observations, including those on gut materials and a comparative study of carbon isotope ratios in chemosynthetic bacteria and mussel tissue (Rau and Hedges, 1979), indicate that the bivalves are able to feed on bacteria directly. Karl K. Turekian and his colleagues at Yale University have estimated (1979) the age of a clam 22 centimeters long at 6½ years, indicating a substantial growth rate.

Chemosynthesis for Aquaculture

From here it is not very far to the idea of using a similar chemosynthetic system for aquaculture. An experimental pilot plant is being built at the Environmental Systems Laboratory of the Woods Hole Oceanographic Institution, under the direction of C.D. Taylor, C.L. Winget, and the author.

The first task, after extensive experimentation, is to design an efficient and trouble-free generator of bacterial biomass. The technical requirements of mixing and controlling the proportions of the liquid and gaseous constituents pose no problem. Figure 4 schematically presents the major parts of such a system.

The fact that shellfish are able to grow on a bacterial diet appears to be amply demonstrated by the populations found around the Galápagos vents. A critical point in our endeavor will arise when it is determined whether or not the system can be run with organisms (bacteria as well as shellfish) occurring in surface waters. Strains of microorganisms from the Galápagos Rift vents are readily available, but whether spat from the deep-sea shellfish will be able to develop at normal pressure is unknown at this time. Small temperature changes may not be detrimental since those measured in the immediate vicinity of the vents ranged from 2.1 (ambient) to 12 degrees Celsius.

Since light is a free source of energy and water a convenient source of electrons, what would be the advantage of a chemosynthetic aquaculture system over one run by photosynthesis? Light is a variable source of energy, and the response of a mixed population to variable growth conditions is complex and often irreproducible. In a chemosynthetic system, all environmental factors could be kept constant. The temperature could be maintained at an optimal level by insulation or installing the plant underground.

Experiments with the regulation of flow rates

of the individual ingredients concern the control of spontaneous oxidation of hydrogen sulfide, the removal of bacterial mats growing on surfaces, and other features of the system. The ability to control conditions could enable us to limit the complexity of the microbial population to such a degree that a very efficient application of a suitable nitrogen source would be possible. In our present experimental project, ammonia is used, which does not preclude the use of other nitrogen sources in later modifications of the system.

What is the advantage of using hydrogen sulfide? It is relatively inexpensive and easily available, and it has never been considered as a possible resource. It is a troublesome waste product of most mining industries. According to a recent book (1979) by John Hunt of the Woods Hole Oceanographic Institution, deeper drilling for natural gas has resulted in higher quantities of hydrogen sulfide — in some cases up to 90 percent. Too expensive as a source for commercial sulfur products, it is most often incinerated and blown into the atmosphere as sulfur dioxide. As such, it is adding considerably to the acid rain pollution. Under these circumstances, any potential use of hydrogen sulfide is of interest. If a use is established, its procurement could be simplified.

Since hydrogen sulfide has a bad odor, a logical question is whether the shellfish in our experiment are edible. The bacterial biomass will not contain any hydrogen sulfide because it will be completely oxidized from the water before it enters the shellfish raceways. In order to replenish the oxygen needed for shellfish respiration, the raceways will be aerated. This will further guarantee that possible traces of hydrogen sulfide will be completely removed and that the major end product of sulfur oxidation will be primarily sulfate (SO_4^{2-}), which will not be harmful to shellfish or the receiving waters.

At this stage, however, the main concern is whether a chemosynthetic generation of bacterial biomass would be feasible and efficient. Only then will it pay to study its application as food for aquaculture.

Holger W. Jannasch is a Senior Scientist in the Biology Department of the Woods Hole Oceanographic Institution.

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Harnessing Power from Tides: State of the Art

by Paul R. Ryan*

Man has been attempting with intermittent success to harness power from tides since at least the Middle Ages and probably earlier. There are records of tidal mills in Gaul, Andalusia, and England in the 11th century. During the late 19th and early 20th centuries, however, the attempts to use this power diminished as relatively inexpensive hydroelectric plants were established along rivers, and central station thermal power plants came into existence. Today, with industrial nations experiencing energy shortages and rising fuel costs, consideration is once again turning to harnessing the tides.

Tidal power is a renewable resource. It requires no expensive fuel and contributes little to environmental pollution. Land requirements are minimal. Plants are safe, reliable, and can remain on stream for a century. On the other hand, construction costs are relatively high, and thus unit power costs are greater than those obtainable from other sources of generation. In addition, since a mean tidal range of more than 5 meters is required for economically feasible operation, sites are limited in number. In the United States, only Cook Inlet, Alaska (7.5 meters), and Passamaquoddy and Cobscook Bays, Maine (5.5 meters) are considered prime prospects for conventional projects. The U.S. Department of Energy, however, is now considering a new approach that can operate in a tidal range of 2 meters and utilizes relatively inexpensive, flexible, lightweight construction materials. In addition, the conversion of energy is accomplished through the use of compressed air. If this concept proves practicable, it could be used in many areas of the world.

Global Tidal Power Prospects

Although total tidal power potential represents only a relatively small portion of world energy requirements, its realization would nevertheless save a significant amount of fossil fuels. Tidal power projects worldwide have been estimated to have a potential energy output of 635,000 gigawatts, the equivalent of more than a billion barrels of oil, a year. By comparison, proposed projects in the United States have a potential energy output of 18,300 gigawatts per year or more than 30 million barrels of oil (the 1977 U.S. oil consumption rate was 18.4 million barrels per day).

Internationally, the areas that appear to hold the most immediate promise are the upper Bay of Fundy, Canada; Chausey in the Bay of Mont St. Michel in France; the Gulf of Mezen in the Soviet Union; the Severn River Estuary in England; the Walcott Inlet in Australia; San José, Argentina; and Asan Bay in South Korea. Of these areas, the most active projects are in South Korea, France, and Canada.

In South Korea, the government is now considering embarking on Phase Two of its tidal power study, having earmarked $2 to $3 million to develop the technical information necessary to build a project. The most promising site at the moment is Asan Bay, where a 450-megawatt plant is envisioned in the inner basin and a 810-megawatt facility in the outer one. Two other locations are also being considered — a 330-megawatt project at Incheon and a similar facility at Garorim. The Phase Two study will last 18 to 24 months.

The most successful utilization of tidal power to date is in France in the La Rance estuary near St. Malo (Figure 1). The French, who began examining the possible development of tidal power in the 1920s, broke ground for the 240-megawatt La Rance plant in 1960 and completed the project in 1967. The plant has performed to all expectations since its completion. Its total annual cost of operation in 1975 compared favorably with peaking power being

*The material in this article is based on interviews with Warner W. Wayne, Jr., Consulting Engineer for Stone & Webster Engineering Corporation, Boston, and Alexander M. Gorlov, Associate Professor in the Department of Mechanical Engineering at Northeastern University, Boston, Massachusetts. It also includes information contained in a paper submitted by Wayne to a 1977 symposium on Energy and the Oceans entitled *The Current Status of Tidal Power: Can It Really Help?*, plus data from the U.S. Army Corps of Engineers — *Tidal Power Study, Cobscook Bay, Maine, Preliminary Report on the Economic Analysis of the Project* (March 1979).

Tides:

obtained from conventional hydroelectric plants at that time.

The French are now re-evaluating the feasibility of establishing a giant two-pool* tidal power station (6,000 to 12,000 megawatts) at Chausey in the Bay of Mont St. Michel, which is not too far from the La Rance station. France is part of a vast Western Europe power network that has substantial hydroelectric reservoirs. Large amounts of tidal power from Chausey could be switched to various parts of Europe as it becomes available, with excess power stored for future use.

In Canada, the government has undertaken a \$33 million study of tidal power, concentrating on three main sites — Shepody Bay, and Cumberland and Minas basins. The study — to be completed in 1981 — envisions the transmission of power to the New England/Quebec area thereby requiring the cooperation of U.S. utility companies for successful augmentation. In the meantime, a modest sized demonstration project using very large Straflo turbine units suitable for large tidal power plants is moving ahead in the Annapolis Basin in Nova Scotia.

DOE Considering New Scheme

Up to now, most efforts to harness tidal power have involved building rigid dams to separate bays with narrow entrances from the ocean. Alexander M. Gorlov, associate professor in the Department of Mechanical Engineering at Northeastern University in Boston, proposes using a very thin plastic barrier — or what he calls a "water sail" — to replace the conventional dam. The U.S. Department of Energy, Division of Advanced Energy Projects, has awarded Gorlov a \$131,000 contract to pursue the idea further — namely to develop plans for a pilot plant that will demonstrate the feasibility of the concept.

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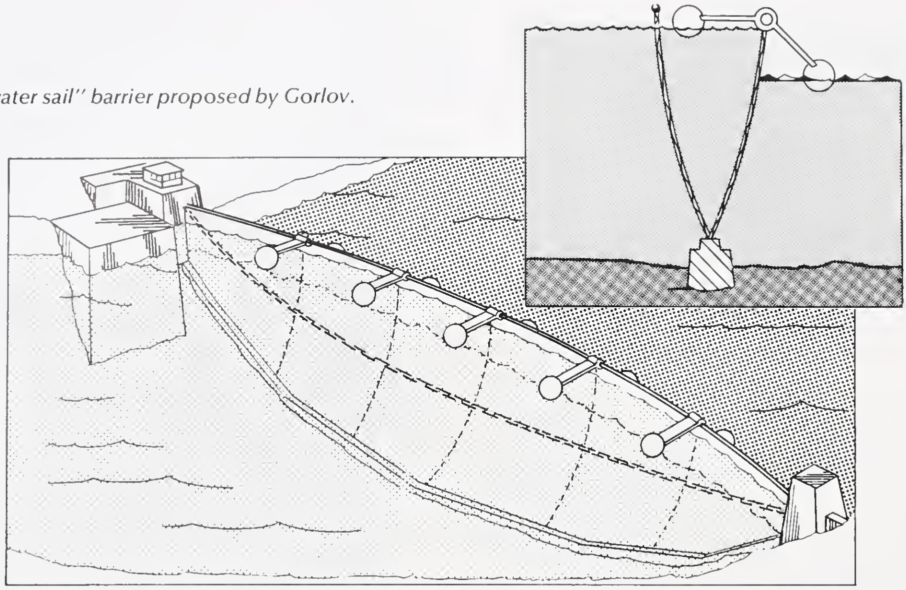
*All tidal power concepts basically fall into the categories of either single or multi-basin projects. They are further divided into single-effect (one-way tide working) and double effect (two-way tide working). The single-effect plan uses either the ebb or flood tide to provide power. The double-effect scheme uses both.

Figure 1. The La Rance tidal power station on the northern coast of Brittany, France. Tides often reach a height of 13½ meters. (Photo courtesy Michel Brigaud, French Embassy)

Figure 2. The "water sail" barrier proposed by Gorlov.



Gorlov's proposal comes on a slack tide for tidal power in general in the United States. In March of this year, the U.S. Army Corps of Engineers concluded a preliminary economic analysis of the Cobscook Bay area in Maine, finding that "tidal power, though more competitive today, is still not justified."

In the novel approach suggested by Gorlov,* the conventional dam would be replaced by a membrane of reinforced plastic that would be hermetically anchored to the bottom and sides of the bay (Figure 2). Thus the membrane — constructed in sections — could be lowered, if necessary, or pulled aside, to allow for ship traffic, or to protect it during storms (Figure 3).

The top of the barrier would be supported by a cable spanning the entrance to the bay. The cable would be fixed to several specially designed floats that would keep the barrier above the surface of the water, maintaining the desired differential level — approximately 2 meters of head between the ocean and basin side — during rising and receding tides.

The underwater part of the barrier would be exposed to a net water pressure equal to the difference in water levels across the dams. It would therefore be called upon to withstand pressure of 2 meters of water or about 0.2 atmosphere (well within the strength limits of today's reinforced plastic material).

Gorlov pointed out in his proposal to the Department of Energy that even if several sections — the size is yet to be determined — of the barrier were to be destroyed for some reason, only leakages would occur, which could easily be repaired. He asserted that the membrane barrier would be particularly immune from landslides and earthquakes as compared to a conventional dam.

The conversion of the tidal energy would be accomplished through the use of compressed air. Two chambers connected to an air motor (large piston) are used in the process (Figure 4). Basically, the flow of water from a higher elevation to a lower one provides the energy to drive the piston. This reciprocating engine arrangement can be used either for the direct generation of electricity or for storing compressed air for later conversion to electricity during peak periods. The possibility of using a gas turbine engine for energy conversion will also be tested for technical and economic feasibility.

Gorlov stated in an interview that the energy output of the dam could be increased by heating the compressed air. He noted that 60 percent of the capital for a conventional dam most often goes for construction of the powerhouse. In his concept, only 15 to 20 percent of that figure would be required. Overall, he estimated that his concept would be "20 to 30 times cheaper" to construct than a conventional tidal project.

Warner W. Wayne, a specialist in tidal power working for Stone & Webster Engineering Corporation in Boston, Massachusetts, commented that no special sluice gates would be necessary for water regulation in Gorlov's proposal, thereby making it even more attractive economically. On the other hand, extremely large pistons would be required to produce significant amounts of electricity. Wayne noted there might be some environmental concerns connected with the project — specifically, the possibility of stagnant water in the basin area behind the barrier. In general though, he felt the project was environmentally clean compared to other conversion methods.

*The approach is grounded in two U.S. patents filed for by Professor Gorlov: No. 4095432, June 20, 1978, and No. 4103490, Aug. 1, 1978.

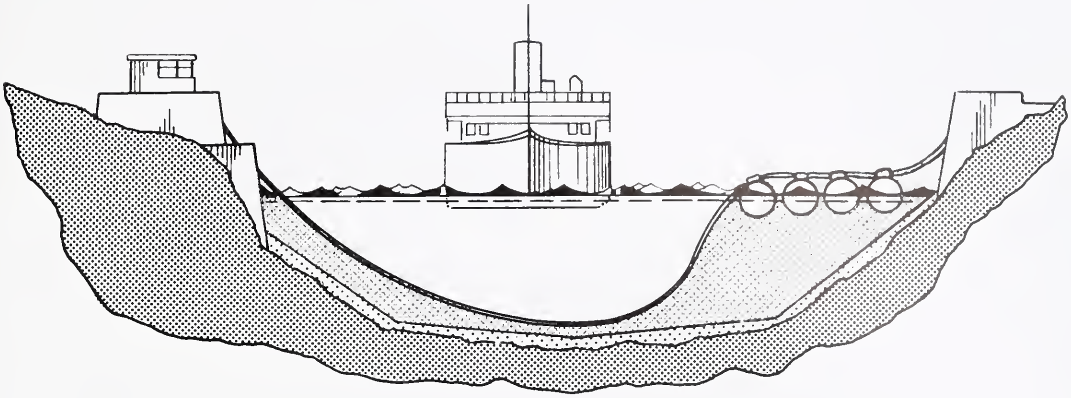


Figure 3. Under the Gorlov concept, the reinforced plastic barrier could be dropped and pulled to one side.

Wayne said Cobscook Bay, Maine, might be a possible site for a demonstration model, but that a specific site had not yet been determined, nor the size of the installation. Gorlov initially envisioned building his pilot project in Boston harbor, running the plastic barrier across from Logan Airport to Winthrop. He is presently investigating 20 different sites in Maine.

The Passamaquoddy-Cobscook area has been considered a possible source of tidal power since 1920 (see *Oceanus*, Vol. 17, Summer 1974, page 30). In fact, construction was actually started in 1935 on a project in Cobscook Bay during President Roosevelt's tenure, but was suspended when Congress failed to vote for additional funding. The Corps of Engineers report mentioned earlier notes that if the project had been completed in 1936, the estimated annual cost over its 100-year life would have been \$2.4 million. Today it would be producing energy at a cost of less than 1 cent per kilowatt-hour.

The U.S. Army Corps of Engineers report of March 1979 covered approximately 90 different tidal power alternatives, utilizing different types of turbine and generator equipment. The sizes of the projects ranged from 5 to 450 megawatts with annual power output of 16 to 790 million kilowatt-hours per year. The construction cost of the projects ranged from approximately \$22 million to \$916 million. Annual operation and maintenance costs varied between \$1.5 million and \$85 million.

The study noted that from an engineering and construction point of view, the proposed projects in the area remained feasible. It added that the projects might have some merit "when some of the current events affecting energy are better known and fully evaluated." Wayne has observed that "the costs of available fuels for alternative sources of generation are assuredly going to rise drastically in the near future, and since tidal plants would be long-lived (75 to 100 years), the economic evaluations of any proposed projects should be based upon 'life cycle' cost analyses rather than on conventional economic analyses (such as the Corps of Engineers report) that mainly consider comparative costs at only one point in time." He warned that unless this type of approach were adopted, many promising tidal power sites that should be developed would be continued to be found "uneconomic."

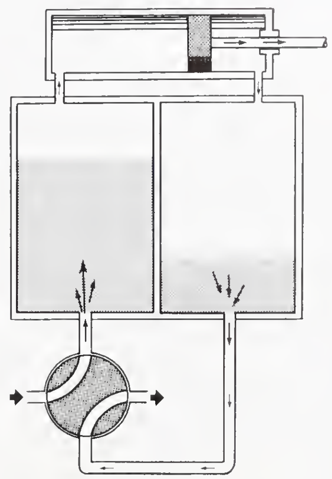


Figure 4. The conversion process, utilizing tidal chambers and compressed air.

Paul R. Ryan is Associate Editor of Oceanus, *published by the Woods Hole Oceanographic Institution.*

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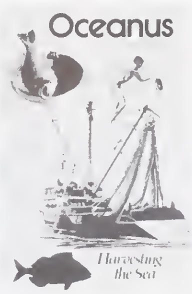

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DEEP-SEA PHOTOGRAPHY, Vol. 18:3, Spring 1975 — A good deal has been written about the use of hand-held cameras along reefs and in shallow seas. Here eight professionals look at what the camera has done and can do in the abyssal depths. Topics include the early history of underwater photography, present equipment and techniques, biological applications, TV in deep-ocean surveys, the role of photography aboard the submersible *Alvin* along the Mid-Atlantic Ridge, and future developments in deep-sea imaging.

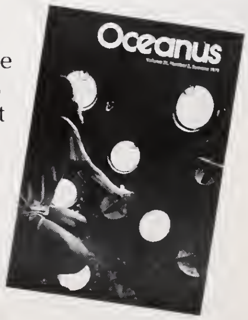
MARINE BIOMEDICINE, Vol. 19:2, Winter 1976 — *Very limited supply.*

ESTUARIES, Vol. 19:5, Fall 1976 — Of great societal importance, estuaries are complex environments increasingly subject to stress. The issue deals with their hydrodynamics, nutrient flows, and pollution patterns, as well as plant and animal life — and the constitutional issues posed by estuarine management.

SOUND IN THE SEA, Vol. 20:2, Spring 1977 — Beginning with a chronicle of man's use of ocean acoustics, this issue covers the use of acoustics in navigation, probing the ocean, penetrating the bottom, studying the behavior of whales, and in marine fisheries. In addition, there is an article on the military uses of acoustics in the era of nuclear submarines.

GENERAL ISSUE, Vol. 20:3, Summer 1977 — The controversial 200-mile limit constitutes a mini-theme in this issue, including its effect on U.S. fisheries, management plans within regional councils, and the complex boundary disputes between the U.S. and Canada. Other articles deal with the electric and magnetic sense of sharks, the effects of tritium on ocean dynamics, nitrogen fixation in salt marshes, and the discovery during a recent Galápagos Rift expedition of marine animal colonies existing on what was thought to be a barren ocean floor.

OIL IN COASTAL WATERS, Vol. 20:4, Fall 1977 — *Very limited supply.*



THE DEEP SEA, Vol. 21:1, Winter 1978 — Over the last decade, scientists have become increasingly interested in the deep waters and sediments of the abyss. Articles in this issue discuss manganese nodules, the rain of particles from surface waters, sediment transport, population dynamics, mixing of sediments by organisms, deep-sea microbiology — and the possible threat to freedom of this kind of research posed by international negotiations.

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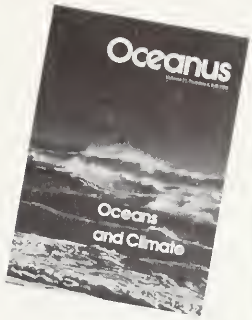

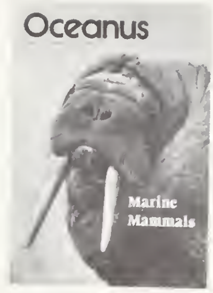

a valuable addition to any marine library

MARINE MAMMALS, Vol. 21:2, Spring 1978 — Attitudes toward marine mammals are changing worldwide. This phenomenon is appraised in the issue along with articles on the bowhead whale, the sea otter's interaction with man, behavioral aspects of the tuna/porpoise problem, strandings, a radio tag for big whales, and strategies for protecting habitats.

GENERAL ISSUE, Vol. 21:3, Summer 1978 — The lead article looks at the future of deep-ocean drilling, which is at a critical juncture in its development. Another piece — heavily illustrated with sharp, clear micrographs — describes the role of the scanning electron microscope in marine science. Rounding out the issue are articles on helium isotopes, seagrasses, red tide and paralytic shellfish poisoning, and the green sea turtle of the Cayman Islands.

OCEANS AND CLIMATE, Vol. 21:4, Fall 1978 — This issue examines how the oceans interact with the atmosphere to affect our climate. Articles deal with the numerous problems involved in climate research, the El Niño phenomenon, past ice ages, how the ocean heat balance is determined, and the roles of carbon dioxide, ocean temperatures, and sea ice.

HARVESTING THE SEA, Vol. 22:1, Spring 1979 — Although there will be two billion more mouths to feed in the year 2000, it is doubtful that the global fish harvest will increase much beyond present yields. Nevertheless, third world countries are looking to more accessible vessel and fishery technology to meet their protein needs. These topics and others — the effects of the new law of the sea regime, postharvest fish losses, long-range fisheries, and krill harvesting — are discussed in this issue. Also included are articles on aquaculture in China, the dangers of introducing exotic species into aquatic ecosystems, and cultural deterrents to eating fish.

GENERAL ISSUE, Vol. 22:2, Summer 1979 — This issue features a report by a group of eminent marine biologists on their recent deep-sea discoveries of hitherto unknown forms of life in the Galápagos Rift area. Another article discusses how scuba diving is revolutionizing the world of plankton biology. Also included are pieces on fish schooling, coastal mixing processes, chlorine in the marine environment, drugs from the sea, and Mexico's shrimp industry.

OCEAN/CONTINENT BOUNDARIES, Vol. 22:3, Fall 1979 — Continental margins are no longer being studied for plate tectonics data alone, but are being analyzed in terms of oil and gas prospects. Articles deal with present hydrocarbon assessments, ancient sea-level changes that bear on petroleum formations, and a close-up of the geology of the North Atlantic, a current frontier of hydrocarbon exploration. Other topics include ophiolites, subduction zones, earthquakes, and the formation of a new ocean, the Red Sea.

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SEA-FLOOR SPREADING, Vol. 17:3, Winter 1974
AIR-SEA INTERACTION, Vol. 17:4, Spring 1974
THE SOUTHERN OCEAN, Vol. 18:4, Summer 1975
SEAWARD EXPANSION, Vol. 19:1, Fall 1975
OCEAN EDDIES, Vol. 19:3, Spring 1976
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